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1 + 1 = 3

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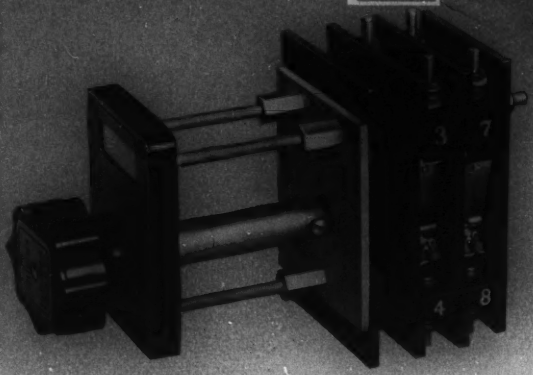

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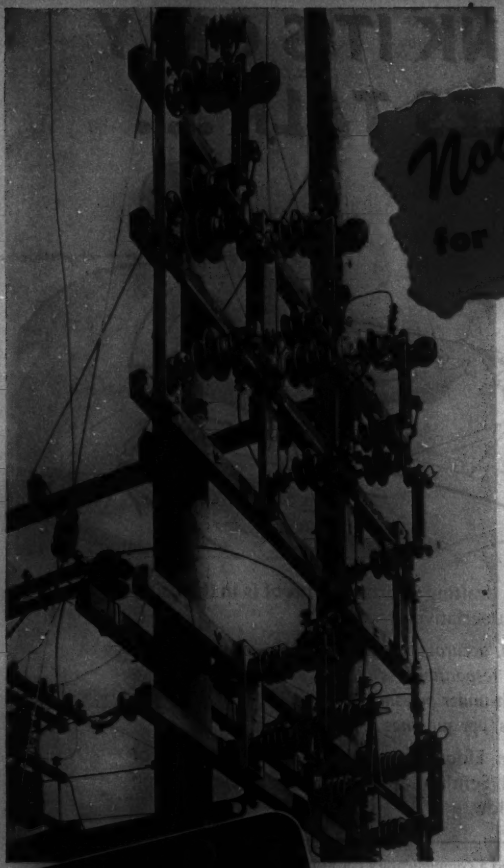

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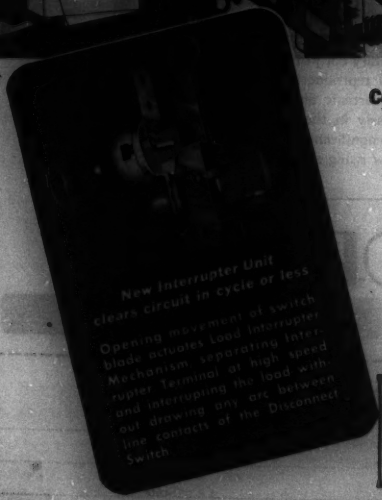
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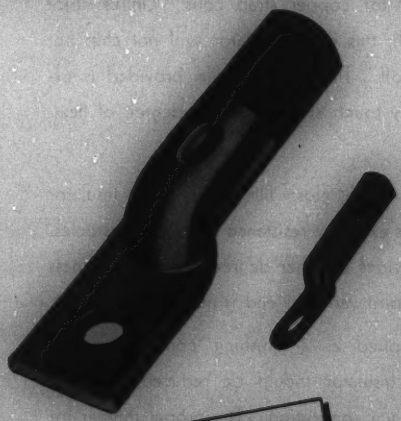

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The Cover: A switching device employed in dial telephone systems, this Federal Telephone and Radio 100-point finder automatically locates and connects with either an available or a preselected circuit.

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ELECTRICAL ENGINEERING
VOLUME 63, NUMBER 12 DECEMBER 1944

The Selenium Rectifier

GLEN RAMSEY
MEMBER AIEE

A concise explanation of the construction and theory of operation of the selenium rectifier is combined with a comprehensive discussion of the effects of various applications on design by the author.

ALTHOUGH the selenium rectifier has been hailed by some as a new development, the photoelectric and rectifying properties of selenium were discovered many years ago. In 1932 selenium rectifiers were being used widely in Europe, and it was in that year that Fansteel Metallurgical Corporation began investigating the possibility of selenium rectifiers for railway signal service. In 1938 commercial production of selenium rectifier plates in the United States was commenced by a subsidiary of the International Telephone and Telegraph Company. The following year Fansteel selenium rectifiers, using International Telephone and Telegraph rectifier elements, were developed and introduced to railway, utility, and industrial users.

Railway signal service is an unusually rigorous test of a rectifier. In this service rectifiers usually operate continuously; located in signal cases along the right of way they are exposed to extremes of summer and winter temperatures, vibration from passing trains, moisture, and moderately corrosive atmospheres. Several thousand selenium rectifiers are operating under these conditions with complete satisfaction.

This article is based upon an intensive study of selenium-rectifier elements, both in the field and in the laboratory, by the author and his associates of the Fansteel engineering staff.

NOMENCLATURE

For clarity, the following terminology is used:

Plate: A single rectifier plate which in itself may be operated as a rectifier.

Element: An assembly of rectifier plates in series, parallel, series-parallel, center-tap or bridge circuit. Rectifier elements usually are made by assembling plates upon a center bolt or stud from which the plates are insulated. Rectifier elements also are called "stacks."

Fin: A square or round metal plate which performs no electrical function but is assembled in the element for the purpose of dissipating heat.

Rectifier: May be a single plate or element, a group of elements, or a complete assembly with transformer and controls.

Valve: A rectifier whose function is not to rectify a-c power but to block the reverse flow of direct current.

Ambient temperature: In general this term refers to the air temperature immediately surrounding a rectifier element. In this article where ambient temperatures are given, they are the temperatures of the air *below* the element, before it has been heated by the rectifier.

The advantages of the selenium rectifier make its use desirable in a very wide variety of applications wherever any type of dry-plate or metallic rectifiers may be used. High operating voltage per junction makes for smaller elements or assemblies of elements. At present selenium plates are being made that will operate at 18 and 30 volts per junction. Blocking layers have been formed to withstand considerably higher voltages. However, they are not available for commercial use. The high current density at which selenium rectifiers may be operated for normal rating, as well as higher efficiency which these factors produce, also contributes to their advantage. Wide temperature ranges can be withstood, a feature which is absolutely necessary in aircraft applications. Selenium rectifiers have long life and low aging properties. As a result of these advantages, the selenium rectifier is well established in the dry-plate rectifier field.

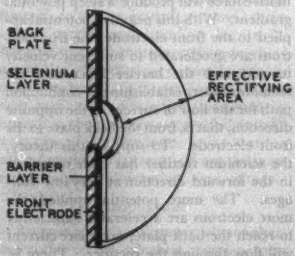

Figure 1. Cross section of selenium-rectifier plate

The field for good dry-plate rectifiers has expanded tremendously with the fast development of electronics resulting from the war. The selenium rectifier has filled these requirements, and, in most cases it is the only rectifier of its type that will meet them. Although we already have applied selenium rectifiers and valves to many new "impossible" tasks, there is no reason to believe that we shall not continue to find more and more uses for them. Exigencies of the war have brought about fundamental changes in engineering philosophy with the result that difficult problems of application now are approached with more confidence.

CONSTRUCTION

The selenium-rectifier plate consists of a nickel-plated steel or aluminum back plate (other metals also may be used), a thin layer of metallic selenium, a barrier layer, and the front electrode (see Figure 1). The back plate acts only as a support. The barrier layer is formed between the selenium and the front electrode. Current flows freely from the back plate to the front electrode but is blacked in the reverse direction. Suitable contact to carry away the current is made to the front electrode by a spring washer or other means (see Figure 2). The selenium rectifier is a one-piece rectifier requiring no high-pressure contact for rectification. As a matter of fact, high pressure on the barrier layer is detrimental. In normal construction, no front electrode is applied to the center of the plate and, subsequently, no barrier layer formed. This permits pressure to be applied to the spacing and limiting washers without affecting the reverse resistance.

A center contactor[4] has been developed whereby the spring (petal) washer is eliminated and a solid contact washer is used (see Figure 3). Contact is made to an area in the center which is covered with an

Glen Ramsey is manager of the rectifier division of the Fansteel Metallurgical Corporation, North Chicago, Ill.

The author expresses thanks to the following of his associates for assistance in compiling the information given in this paper: C. E. Holmes, Paul C. Dolken Stanley Fry, and James H. Hall.

insulator and additional front electrode over the insulated area. In the forming process no barrier layer is formed at this point, and no change in reverse resistance will result from pressure exerted on the assembly.

Plates are assembled on bolts in the proper order for the rectifier assembly required. As many as 24 to 40 plates may be assembled on one bolt, depending on size of plate and the plate spacing. Plates sizes vary from less than one inch in diameter to 4⅜ inches. Other plates larger or smaller are made for special applications.

Selenium-rectifier plates are insulated from the center bolt by insulating tubing. In regular production, elements having 90 or less volts output are insulated for 600 volts alternating current. For output voltages above 90 elements are insulated for 1,500 volts alternating current. Insulation on the elements alone can be furnished up to 3,000 to 4,000 volts. Further insulation generally is accomplished in the mounting brackets.

For explanation purposes the selenium rectifier may be considered as a resistance device which has a very high resistance in one direction and a low resistance in the other. Current passes freely in the forward direction (low-resistance direction), but only a very small current will flow in the reverse direction under normal operating conditions.

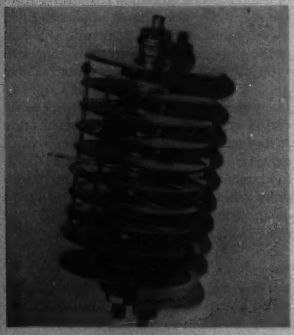

Figure 2. Selenium rectifier with spring washer

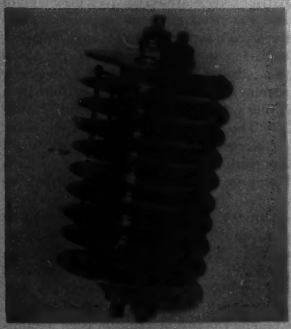

Figure 3. Selenium rectifier in which the spring washer has been replaced by a solid contact washer

THEORY OF OPERATION

The next logical question is: "What causes these asymmetrical characteristics"? In other words, "What makes it a rectifier"? Because of divided opinions on this phenomenon no attempt will be made to offer any new theory. One of the best and most logical explanations has been given by E. A. Richards,[4] which follows.

Any dry-plate or metallic rectifier must consist essentially of a semiconductor, a barrier layer, and a good conductor, the barrier layer being an insulator through which electrons can pass in either direction.

In the selenium rectifier, the semiconductor is the selenium, the front electrode is the good conductor, and the barrier or insulator layer is formed between the two. If the selenium rectifier is compared to a cold-cathode-emitter rectifier, the front electrode is the cathode, the back plate the anode, and the selenium and barrier layers the insulator between the two.

Considering the electron theory, the action can be described as follows: In the good conductor (front electrode) there is an abundance of free electrons (see Figure 4). In the semiconductor, selenium, the number of free electrons is very small. When negative-electron potential is applied to the good conductor (front electrode) and opposite polarity to the back plate, an electric field is set up across the barrier layer. Because of the fact that the barrier layer is extremely thin, a small electromotive force will produce a steep potential gradient. With this negative potential applied to the front electrode, the free electrons are accelerated to sufficient velocity to penetrate the barrier layer and the selenium layer, establishing a conduction path for the flow of current in the opposite direction, that is, from the back plate to the front electrode. To support this theory, the selenium rectifier has high resistance in the forward direction at very low voltages. The more potential applied, the more electrons are accelerated sufficiently to reach the back plate, and more current will flow through the rectifier. There is, of course, a limit to the voltage which may be applied (see Figures 5 and 6).

If the polarity is reversed, a different condition exists. Then the semiconductor (selenium layer) has to produce the free electrons. There being only a few free electrons in the selenium, only a very few will be able to penetrate the barrier layer and make contact with the front electrode. As a result, only a very small current will flow. This is called "reverse current" or "back leak." Study of a back-leak curve (Figure 5) discloses that as the reverse voltage is increased, the back leak increases. This may be carried to a point where rupture occurs because of the tremendous voltage gradient at a point where free electrons are present.

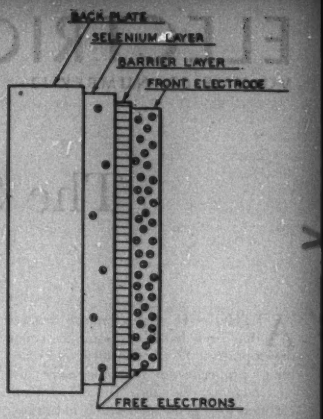

Figure 4. Proportion of free electrons in the good conductor and semiconductor layers of the selenium rectifier

If this explanation of the operation be correct, then it can be assumed that thickness of the selenium layer will be a factor in the performance of the rectifier. This has been found to be the case, the forward resistance being a function of the selenium and barrier layer and the front electrode, the reverse resistance the function of the barrier layer.

The barrier layer is probably the most important part of the rectifier as far as performance and stability are concerned.

After the selenium has been applied to the back plate, the selenium surface exposed is treated specially to produce the best and most stable barrier layer. The plate then is masked at the outside edge, and the center and front electrode applied. The front electrode is a special metal alloy which in conjunction with the selenium and through subsequent treatment produces an effective barrier layer. When the plate is completed mechanically, it is formed electrically by applying direct, alternating or pulsating-direct current in the reverse direction until the reverse current reaches a predetermined value. Besides forming a stable barrier layer, this process cleans the selenium of any concentration of free electrons too close to the front electrode. This cleaning process may be evident on the surface of the front electrode in the form of a tiny rupture at the point of high concentration of free electrons in the selenium. This does not affect the performance of the rectifier. The forward resistance increases slightly during the formation process.

Rectifiers left idle for long periods of time may relax, and, when tested at low

voltage, may have low reverse resistance. When full voltage is applied, the normal reverse resistance is restored at once. There is, however, enough lag to give high instantaneous currents. In practically all rectifier applications this may be disregarded. However, on sensitive valve applications it must be taken into account. Sometimes this characteristic is desirable, sometimes not, depending upon the application.

If the rectifier is abused, either by overvoltage or current overload, especially in battery-charging applications, permanent damage can be done to the barrier layer. This, of course, results in high a-c and d-c back leak. After damage of this nature, no amount of normal operation or forming process will restore the damaged barrier layer.

GRADING OF PLATES

Selenium rectifier plates are graded by forward and reverse resistance and according to the type of rectifier circuit.

Grading by forward resistance is probably the most important, as plates that are operated in parallel should be matched properly to prevent unequal current distribution. Slight variation in forward resistance can be tolerated, however, as those plates with lower resistance will balance with the other plates as the rectifier ages.

Although keeping the reverse resistance high is important, it produces no effect, except heating, in most circuits. In half-wave rectifying circuits the output voltage across the load is affected by the reverse resistance of the rectifier because of the subtracting effect of the reverse current through the load. This condition does not occur in other circuits.

Plates are so graded and assembled into elements to produce a mean value of output voltage at the plate rating within plus or minus five per cent for resistance or inductive loads.

Only plates of the same size can be connected together whether in series or parallel. To do otherwise would produce an unbalance of current in the plates which would cause the smaller plates to carry more than their normal capacity.

It is not recommended that elements be reassembled, once they have been assembled for a specific application.

PROTECTIVE COATING

In general atmospheres which will damage other electrical equipment will have similar effects on selenium rectifiers unless they are properly protected. Fortunately, all of these conditions can be overcome, even to the extent of immersing the rectifier in oil.

Probably the worst offenders against selenium rectifiers are mercury, salt, and fungi. Coatings are available to protect against these conditions. Rectifiers generally are coated before they leave the factory except when for special reasons the coating is omitted. The coatings, however, are no better than the manner in which they are applied and handled, after the rectifiers are finished. Care must be taken not to damage the finish in handling, for once the finish has been scratched through, the rectifier is vulnerable to attack.

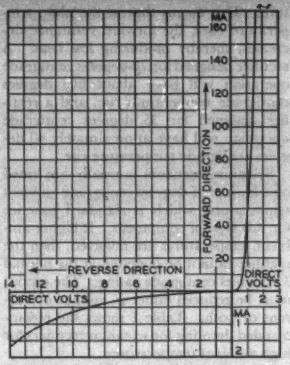

Figure 5. Static characteristic of a selenium-rectifier disk with an effective surface area of one square centimeter

Users of rectifiers should not apply ordinary lacquers or other surface finishes to an unfinished rectifier, or to one that has been coated, without consulting the supplier. It is possible that the finish may be destructive, if applied directly to the plates or in combination with the finish already on the plates.

EFFICIENCY

The selenium rectifier has the advantage of high efficiency which is maintained over a wide range of output. Efficiencies range from 65 to 85 per cent, depending on the type of circuit and load (see Figure 7). Because of the nonlinear resistance characteristics, the efficiency remains practically constant from 20 per cent to 140 per cent load. Best efficiency is obtained by operating the rectifier as near full voltage as is practical. The losses in the rectifier are a function of current and are the same for all values of alternating input voltage.

REGULATION

Because of the nonlinear resistance characteristics of the selenium rectifier, most of the output voltage regulation occurs between zero and 20 per cent load. Therefore it is desirable, if regulation is important, to operate the rectifier between 20 and 100 per cent load.

In most applications this can be taken care of by selecting the proper capacity rectifier, so that the minimum load on the rectifier will be between 15 and 20 per cent. The actual *no-load* condition is never of any importance, because at this condition the output of the rectifier will not be connected to any load. If conditions are such that the minimum load is below 15

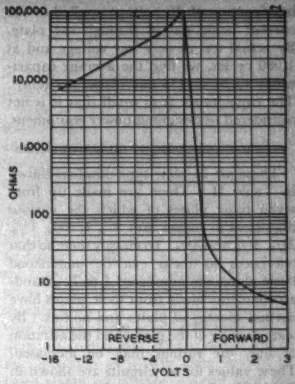

Figure 6. Static resistance characteristics of selenium rectifier disk with a surface area of one square centimeter

Test made on one-inch-diameter plates

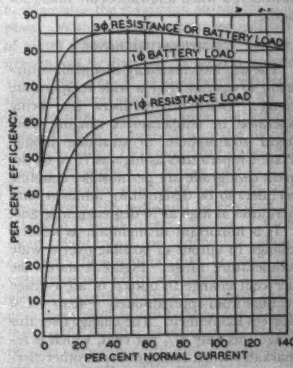

Figure 7. Efficiency of selenium rectifier at full voltage per plate

per cent and close regulation is necessary, then a bleeder load or other means of control must be used.

The fact that over half the regulation occurs in the first 15 to 20 per cent of load makes possible good regulation over 80 per cent of the load range.

Regulation of the rectifier can be calculated from the voltage-drop curves in Figure 14, by selecting the voltage drop at the minimum and maximum load condition and solving for the direct voltage. Regulation on various sizes of plates and loading is between 8 and 17 per cent from zero to 100 per cent load.

CAPACITANCE

Although selenium rectifier plates have capacitance, under practically all conditions the small capacitance present can be neglected. The capacitance per unit area

is a function of the voltage applied or the current being passed through the plate. By actual test at very low voltage and at 1,000 cycles, we find the average capacitance to be 0.0155 microfarad per $(cm)^2$. The capacitance is so small that it is not considered in designing power equipment.

VOLTAGE AND CURRENT CHARACTERISTICS

There are 21 plate-type numbers shown in Table II. These are made up from seven basic plates of which the various diameters in inches are: 1/2, 1, 1 1/8, 1 1/2, 2 1/8, 3 1/2, and 4 1/2. To classify them so that references to them can be understood basic plates are numbered 1 to 7. Standard elements made from these plates have normal spacing of plates and no fins. By wide spacing of the plates and the addition of fins, the ratings may be increased. These values for all circuits are shown in Table II. By increasing the rating of a plate in this manner, the efficiency of the rectifier may be expected to be reduced slightly because of increased voltage drop at the higher rate. This also must be considered when allowances are made for aging.

TEMPERATURE RANGE

The war has created a demand for equipment to operate over a wide temperature range. Selenium rectifiers are being operated in temperatures ranging from frigid stratosphere to steaming jungle. Plate temperatures as high as 75 to 85 degrees centigrade are permissible, enabling rectifiers to be designed for ambient temperatures as high as 70 degrees centigrade.

It is important to maintain as small a change in output as possible over a wide temperature range. Figure 8 shows the per cent change in output of an average rectifier from approximately −40 to +130 degrees Fahrenheit. The change over this range was only 8 1/2 per cent, which is remarkable when compared with other electrical devices. Figure 9 shows the a-c and d-c leakage versus temperature. At full alternating and direct voltages, the leakage currents increase at low temperatures. This high leakage is of no concern, however, since it is reduced to normal as soon as the plate reaches normal temperature from either increased ambient or plate temperature rise from leakage current. At half voltage the d-c leakage is practically constant. All bridge rectifiers used to charge batteries will be required to block approximately one half of the plate direct-voltage rating, as in each single or three-phase bridge rectifier, the direct voltage is blocked by twice as many junctions as there are series junctions in each arm. Therefore, d-c leakage will not be affected to any extent by temperature changes in bridge-rectifier circuits. In resistance and inductive loads there is no problem of d-c leakage.

Unlike ordinary resistance devices, selenium rectifiers have negative coefficient of resistance with respect to temperature. This means that as the plate temperature rises, the forward resistance decreases, thereby producing less heat. A rectifier designed for 70-degrees centigrade operation will have about five degrees centigrade temperature rise, and a rectifier designed for 35 degrees centigrade operation will have approximately 40 degrees centigrade temperature rise.

Selenium rectifiers normally are rated on a basis of 35 degrees centigrade ambient temperature, which is standard practice for this type of equipment. If higher ambient temperatures are involved, then the rectifier cannot be operated at the normal 35 degrees centigrade rating. The output must be reduced either in voltage or current or both. Table I shows the recommended derating for selenium rectifiers for high ambient temperatures.

Since plate temperature and temperature rise above ambient temperature influence the life and performance of rectifiers, it is worth while to mention a few construction characteristics in which temperature is involved.

Close spacing of plates on the center bolt retards heat dissipation, of course. Rectifier stacks have normal ratings at normal spacing. These ratings can be, and often are, exceeded by spacing the plates at two to three times the normal spacing.

The number of plates in a single element also has an effect on the operating temperature. Stacks of few plates have less temperature rise than those with a large number of plates. The ratings of the plates listed in Table II are based on the maximum number of plates per element.

When rectifier elements are mounted in cabinets with other heat-generating apparatus, they should be arranged in such a manner so that the heat from the other apparatus does not pass over the rectifier or radiate to it. In other words, the rectifier should be mounted below the other apparatus and in such a position that the free flow of air through the element is not impeded. Stacks always should be mounted with the plates parallel to the flow of air through the cabinet. Cabinets should be so ventilated that air may enter the bottom and leave at the top or at some point above the rectifier stack. The chimney effect of this arrangement is helpful in maintaining good operating temperatures.

High-current rectifiers sometimes present loss problems which may result in heat because of eddy-current losses in the steel housing. In such cases busses and rectifier stacks carrying heavy currents should be located so that the field set up by the current does not reach the steel housing. This is especially important in oil-cooled rectifiers, since the resultant heat will raise the temperature of the oil.

Wherever possible, the rectifier should be mounted in the coolest location, and the maximum ambient likely to be encountered always should be considered.

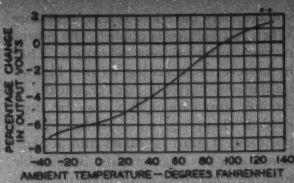

Figure 8. Change in voltage output with ambient temperature for a selenium rectifier with normal resistance load

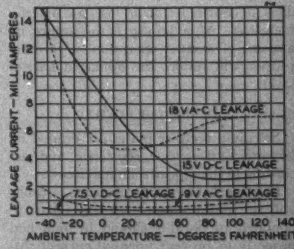

Figure 9. Effect of temperature on alternating and direct leakage current for a number-2 selenium-rectifier plate

It has been observed that the forward resistance is increased permanently, if the rectifier is subjected to temperatures below −40 degrees centigrade for extended periods of time. Temperatures below −40 degrees centigrade rarely are encountered, and no accounting is normally necessary.

For applications below −40 degrees centigrade the rectifiers must be stabilized for the minimum temperature and then regraded before the elements are assembled. This is especially true for regulator applications.

SHORT-DURATION OPERATION

There are many applications of rectifiers for intermittent service of short duration. In these applications it will not be necessary to choose a rectifier having current capacity sufficient for continuous operation. The amount of overload which can be applied naturally will depend upon the duty cycle.

Selenium rectifiers may be operated at overloads up to eight to ten times normal current, depending upon the circuit application and time allowed for the rectifier to return to normal temperature.

The current value at which a selenium plate may be operated for short periods is governed by the time required for the plate to reach its maximum temperature and the voltage drop and losses permissible in the element. When rectifiers are designed for intermittent service, the time cycle of load "on and off" periods must be taken into account, as this has a direct

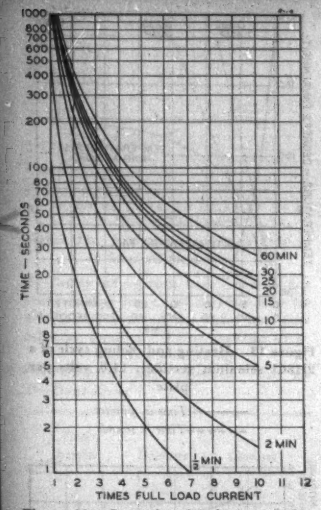

Figure 10. Operating time in seconds for a selenium rectifier at various overloads and cooling periods with ambient temperature 95 degrees Fahrenheit

Cooling time is given in minutes

bearing on the cooling and, consequently, the actual current rating.

In this service, the maximum voltage ratings of the plates cannot be exceeded, even for very short intervals. The *no-load voltage* impressed on the input a-c terminals of the element therefore governs the alternating-voltage rating of the element. Where the a-c circuit is switched with the load on, the load alternating input voltage governs. The maximum alternating voltage which may be applied to the rectifier always must be determined, and the rectifier designed for this voltage.

Normally the plates should not be operated at currents greater than five to seven times normal ratings, as the resultant voltage drop and losses in the element are high above this point.

There are so many factors to consider in this type of service that it is a little difficult to make any general rule apply. Therefore, separate consideration of each of these applications is preferred and, if necessary, actual test runs. However, a group of curves shown in Figure 10 has been prepared which will give an approximate time and overload factor providing that the off period is known. However, one may work directly from the curve. This curve also considers the maximum number of plates per stack. Figures 11, 12, and 13 show characteristics of specific rectifier combinations. The rectifiers used in Figures 11 and 12 were operated half wave, and consisted of one plate each. The rectifier used in Figure 13 was operated half wave and was made up of eight plates.

RECTIFIER-ELEMENT DESIGN

The direct output voltage of any rectifier is equal to the alternating input voltage minus the voltage drop in the rectifier, which results from current passing through the plates, divided by the form factor for the particular circuit. For explanation purposes, single-phase half-wave and single-phase-bridge rectifiers will be considered to be operating into a resistance load of one ampere.

Single-Phase Half Wave. The formula for single-phase half wave is

$$E_2 = \frac{E_1 - ND}{2.3}$$

where E_2 is direct output voltage, E_1 is alternating input voltage, N is the number of plates in series (in this case one plate is considered), and D is the voltage drop per plate at the current at which the rectifier is operating. The value of D is taken from a voltage-drop curve, which will be explained later. In this example $D=1$. The value of 2.3 is the form factor for a single-phase half-wave rectifier operating into a resistance load. The maximum alternating input voltage per plate is 18, and this value will be used. Therefore,

$$E_2 = \frac{18 - 1 \times 1}{2.3}$$

or approximately 7.4. This same formula is used for inductive loads. The direct output voltage will vary slightly depending on the characteristics of the transformer used, but generally the foregoing is correct.

To go back to the problem, in which the direct output voltage has been determined; Before selecting a transformer, the alternating current required as well as the voltage must be known. Without going into the mechanics of the a-c to d-c ratio, one notes that I_1 is 1.57 times I_2 for resistance loads or 1.57 amperes. For explanation of a-c to d-c ratios in rectifiers, see reference 8. Therefore, an a-c input of 18 volts with 1.57-amperes capacity is needed. In half-wave rectification there is a lagging power factor, because only half of the a-c wave is rectified. Therefore, wattless current to the extent of the power factor is present.

Table I. Rectifier Rating at Elevated Temperatures

Ambient Air Temperature		Recommended Current, Per Cent of Normal	Recommended Voltage, Per Cent of Normal
Degrees Centigrade	Degrees Fahrenheit		
Up to 35	95	100	100
40	104	83	100
40	104	100	80
45	113	67	100
45	113	83	80
50	122	47	100
50	122	67	80
55	131	47	80
55	131	67	60
60	140	30	80
60	140	47	60
65	149	30	60
65	149	47	40
70	159	30	40

Because of the poor power factor of half-wave rectifiers, they are not generally used on high-power units but are confined to low-capacity applications where economy or the half-wave characteristic is desired.

For battery charging the same formula is used except with a different form factor and a different value for D (see Figure 14). In battery charging and capacitive loads the transformer characteristics have more effect upon the output voltage than in resistance load. It is, therefore, generally wise to make some actual tests before final design is completed. This is not as severe an injunction as it may seem, except in cases where no voltage control over the input of the rectifier is provided. The alternating input voltage is generally controllable over a sufficient range to obtain maximum and minimum currents.

The foregoing example was worked out to determine the maximum output for one plate. With this information the number of plates required for any voltage can be determined by dividing the desired output voltage by 7.4. If 74 volts were wanted, then ten plates would be required for a new rectifier. To this must be added enough plates to take care of the aging. With ten plates 180 volts must be applied, and, if an increase of 50 per cent in forward resistance is allowed for aging, approximately 186 volts will be required to maintain 74-volt direct current. One more plate must be added to allow for this. This method may be used for every type of circuit, considering a "unit element," with one plate in each arm, as a base and is satisfactory for determining the number of series plates for all rectifier circuits operating into resistance or inductive loads. The same applies for battery charging and capacitive loads except for single-phase half wave and three-phase half wave. In these two cases the battery or capacitance is in series with the alternating voltage additively on the blocking half of the cycle causing the plate to block the direct voltage plus the alternating voltage. Therefore, sufficient plates must be used to withstand the direct voltage plus the alternating voltage in these two cases.

Single-Phase Full-Wave Bridge. If the same reasoning as was used for half wave is applied, the maximum direct output voltage from a unit bridge having one plate in each arm can be determined. As before and for simplicity, we will consider a plate having a normal basic rating of 1.0 ampere, and a voltage drop D of 1.0 volt. The formula for single-phase bridge circuit operating into a resistive or inductive load is

$$E_2 = \frac{E_1 - 2 \times N \times D}{1.15}$$ (see Figure 15).

It will be noticed that in this formula the product of the number of plates in series and the voltage drop per plate is multiplied by two instead of one for the half-wave rectifier. When the path of the direct current is traced from one side of the alternating current to the other, it is found that the current travels in the forward direction through two plates instead of one. We, therefore, will get twice the drop of one plate.

When the equation is solved for E_3, and 18 is substituted for E_1, 1 for N, and 1 for D,

$$E_3 = \frac{18 - 2 \times 1 \times 1}{1.15} \text{ or } 13.9$$

In final design the aging factor will be taken care of as before.

The a-c to d-c ratio for single-phase bridge rectifier and a resistance load as taken from Figure 15 is 1.11. Therefore, the alternating input current will be 1.11 amperes for each ampere direct current.

For battery charging or capacitive load the formula given in Figure 15 is used. When the back voltage is considered applied to the rectifier plates in the bridge rectifier, the maximum direct back voltage per plate will be the direct voltage divided by twice the number of series plates in each arm. In the case of a unit bridge it will be two. Therefore, we cannot apply excessive direct voltage to a bridge rectifier from the battery which it will charge.

The a-c to d-c ratio is always higher for battery charging and capacitive loads for all single-phase and three-phase half-wave circuits.

The form factor on three-phase circuits is the same for resistive, inductive, and capacitive loads.

In selecting a rectifier element for a certain output the direct voltage and current required must be considered. For economic reasons the largest plate generally always should be used to obtain the current required. For instance, if a single-phase bridge rectifier were wanted to deliver 12 volts direct current at 1.2 amperes to a resistance load, this would be the procedure:

First the proper plate size is selected from Table II, which in this case would be a number 5 plate, basically rated at 1.2 amperes for a bridge circuit. Next, we figure the maximum direct voltage obtainable from a unit bridge. To do this we must get the value for D from Figure 14. As this is a basic-rated plate, 1.2 amperes is normal current, so we take the value for D at 1.0 times normal current, or approximately 1.0. The constant for the number 5 plate in Figure 14 is 1.0. The value for D is therefore 1.0. By applying the formula, 13.9 volts direct current is obtained. Therefore, a unit bridge of number 5 plates will be satisfactory. Twice as many number 4 plates or four times as many number 3 plates could have been substituted. This would mean two unit bridges of number 4 plates or four unit bridges of number 3 plates. A better description of these three combinations would be: a bridge rectifier of number 5 plates having one series plate, one parallel plate; for number 4 plates one series, two parallel; and for number 3 plates one series, four parallel.

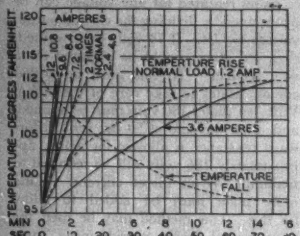

Figure 11. Heating and cooling cycle of a 6H1Al selenium rectifier operated at 18 volts alternating current from normal load to ten times normal load

Time in seconds
Time in minutes

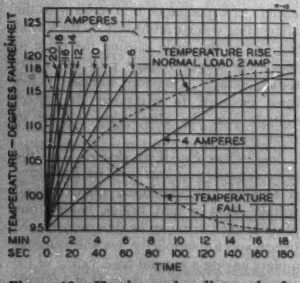

Figure 12. Heating and cooling cycle of a 7H1Al selenium rectifier when operated at 14 volts alternating current from normal load to ten times normal load

Time in seconds
Time in minutes

BATTERY CHARGING AND CAPACITIVE LOADS

In selecting rectifiers for battery charging or capacitive loads, the same general procedure is followed as for inductive or resistive loads, except that the output of the basic rating must be reduced 20 per cent for single-phase rectifiers. This may be accomplished by derating voltage or current or both. In general, it is preferred to derate voltage. No derating is necessary for battery charging or capacitive loads, when three-phase rectifier circuits are used. The same form factor is used in calculating a-c input for all types of loads in three-phase circuits.

Battery chargers having choke input filters may be calculated on basis of inductive or resistive load as far as plate rating is concerned.

In Table III are listed some of the fundamental characteristics of rectifiers for the different circuits for resistive and inductive loading.

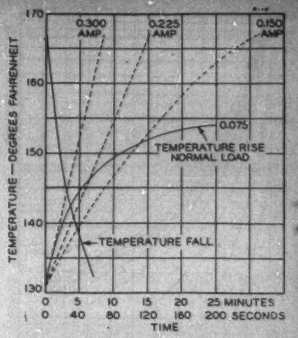

Figure 13. Heating and cooling cycle of a 2H8Cl selenium rectifier, 14.6 volts per plate

Time in minutes
Time in seconds

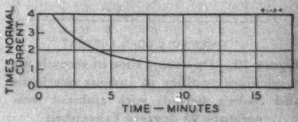

Figure 13A. Time of 2H8Cl rectifier operation to reach 167 degrees Fahrenheit with 131 degrees Fahrenheit ambient temperature at various loads

FORCED COOLING

Selenium rectifiers are normally (basic) rated at approximately 0.160 amperes per square inch at 35 degrees centigrade ambient temperature. By wide spacing and the use of fins the current density is increased to approximately 0.400 amperes per square inch. Higher current densities sometimes are used, but they require special consideration. The density is determined by the nature of the application with respect to temperature, duty cycle, and load characteristics.

Fan cooling may be employed to maintain safe rectifier-plate temperature on rectifiers that are operated at currents above their normal rating, or for protection in high ambient temperatures. The amount of air required to cool the rectifier can be calculated easily, and for all practical purposes 90 to 100 linear feet per minute is sufficient for two times normal rating, and 160 to 180 feet per minute for three times normal rating. The air actually must travel past the rectifier at these rates, if it is to carry off sufficient heat. It is well to remember the effect of obstructions in the path of the air stream upon the air velocity of a fan system which is rated in free air. The path of the air stream should be as free as possible, except for the

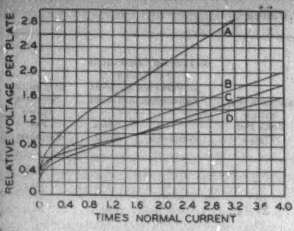

Figure 14. Approximate voltage drop in forward direction

A—Battery and capacitive load: one-phase half wave, one-phase bridge, and one-phase center tap
B—Resistance and inductive load: three-phase half wave, one-phase half wave, one-phase bridge, and one-phase center tap
C—Three-phase bridge, three-phase center tap
D—Direct current

Plate Number	Diameter	Constant
1	1/4	1.1
2	1	1.1
3	1 1/8	0.95
4	1 1/4	1.0
5	2 1/4	1.0
6	3 1/8	1.25
7	4 1/8	1.30

rectifier stacks which are being cooled. We recommend 200 to 250 feet per minute under all conditions, which should provide an ample margin of safety.

Selenium rectifiers may be immersed in oil for operating at increased loading or for operation in destructive atmospheres. Oil-cooling systems are considerably more expensive than fans and are, therefore, not generally considered. Our oil-immersed rectifiers so far have been confined to applications where the rectifiers have had to be protected against very corrosive atmospheres.

For applications where heavy overloads are experienced for short durations, the thermal capacity of an oil-cooled unit affords much more protection to the rectifier than can be obtained by fan cooling.

RECTIFIER AGING

Selenium rectifiers have the most stable output over extended periods of time, when compared with other types of dry-plate or metallic rectifiers. At normal operation the change in output is so small that in many cases no compensation for aging is necessary. This makes possible the elimination of a special transformer on those applications, and the rectifier may be operated directly from the a-c line.

The output of a selenium rectifier will decrease from five to ten per cent, when operated normally and at its basic 35 degrees centigrade rating. Naturally, if the same rectifier is overloaded, the percentage of loss in output will increase. The time required to produce this aging effect is a function of temperature, loading, circuit, and duty. No appreciable aging has been observed in idle rectifiers. Rectifiers not operated for long periods of time may show a slightly lower initial output, but this comes back to normal in a short time. In general, we have found that rectifiers operated at normal rating will reach maximum aging within 20,000 hours of continuous service. The characteristic may and does vary from one to another application. Some rectifiers will show no aging for 2,000 or 3,000 hours, whereas others show a steady aging rate. The fact that current through the rectifier is required to stabilize it may explain the difference in time required to produce stability. Apparently a sufficient number of ampere-hours must pass through the rectifier to produce final stabilized output, which accounts for the longer aging time on intermittent duty applications.

An example will explain best how aging occurs. In this aging or stabilization process, which amounts to approximately six per cent in output, the forward resistance increases approximately 50 per cent. Consider a single-phase bridge rectifier with one plate in each arm. If the normal-rating voltage drop is 1.0 volt and the single-phase bridge formula

$$E_{DC}=\frac{E_{AC}-2\times N\times D}{1.15}$$

is used, where E_{AC} = alternating input volts, N = number of series junctions in each arm, and D = voltage drop at the particular current density. E_{DC}, therefore, = 13.9. After aging, D will equal 1.5 and substituting again E_{DC} = 13.05. The aging in this case is approximately six per cent.

If the same rectifier is operated at three times its normal rating, as could be done in force-cooled rectifiers, D becomes 1.68 volts for a new rectifier. E_{DC} = 12.75. After aging, $D = 1.5\times 1.68$ or 2.52; E_{DC} = 11.25. The output drops 11.5 per cent. This same rectifier, if operated at 100 per cent rating, still will show a six per cent loss in output.

Therefore, it sometimes may be necessary to consider the aging factor in the application of rectifier stacks and to allow enough for the aging which may be expected, depending on the loading of the rectifier plates.

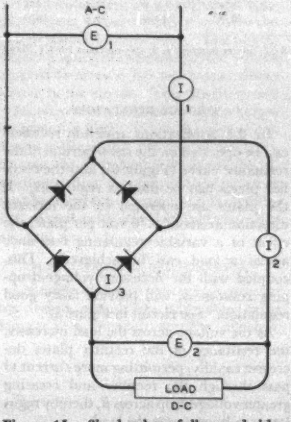

Figure 15. Single-phase full-wave bridge rectifier

Voltage and current values:
E_1—Alternating input voltage
E_2—Direct output voltage
I_1—A-c input amperes
I_2—D-c output amperes
I_3—D-c amperes each arm of rectifier circuit

Voltage values:

Resistance and inductance load, $E_2 = (E_1\times 1.15) + 2ND$

Resistance and inductance load, $E_2 = \frac{E_1 - 2ND}{1.15}$

Current values:

Resistance and Inductance Load	Rms Output Current
I_2 I_1 I_3	
1 . . 1.1 . . 0.5	1.11

Rectifier application—D-c output, 12 volts, 1.2 amperes, load, resistance
Solution—Use 5B1A1 stack; $N = 1.0$; $D = 1.0$; $E_{AC} = 12\times 1.15 + 2\times 1.0\times 1.0$; $E_{AC} = 15.8$

VALVES

There are many circuits in use where valves are required to prevent the flow of current in case of a reversal of polarity. Selenium rectifiers are being applied to these applications successfully.

Each application must be considered individually, since there are inherent characteristics in the selenium plate which must be taken into account. If the application is one wherein the current flows through the selenium plate in the forward direction most of the time and only infrequently is there any back voltage applied, we must remember that at the instant of reversal of voltage, we will get high-leakage currents. This condition lasts only for a very short time, until the leakage current returns to normal. The initial leakage current may run as high as ten to 15 per cent of the normal current at full direct voltage per junction. If this is outside the limits that can be tolerated, then the back voltage per junction must be reduced by adding more plates to a point where operation is satisfactory.

Applications where alternate polarities are applied to the valve are most satisfactory.

A voltage-drop curve for d-c applications is shown in Figure 14.

The d-c ratings of all the plate sizes are

Table II. Sizes and Ratings of Selenium-Rectifier Plates

Plate Type, Number	Plate Diameter, Inches	Disk Size, Number	Fin Size, Number	Maximum D-C Amperes Continuous Output of Element With One Plate Per Arm at Ambient Temperature 95 Degrees Fahrenheit (35 Degrees Centigrade) or Less					Maximum Alternating Volts Per Plate	Maximum Continuous D-C Rating as Valve 95 Degrees Fahrenheit Ambient		Maximum Number Plates Per Element
				Single Phase		Three Phase				Amperes	Block Volts	
				Half Wave	Bridge or Center Tap	Half Wave	Bridge	Center Tap				
1	3/8	1		0.040	0.075	0.100	0.110	0.130	18	0.06	15	36
2	1	2		0.075	0.150	0.200	0.225	0.270	18	0.12	15	36
20	1	2		0.110	0.220	0.290	0.330	0.400	18	0.17	15	28
3	1 1/8	3		0.150	0.300	0.400	0.450	0.550	18	0.23	15	36
21	1 1/8	3		0.290	0.450	0.600	0.670	0.820	18	0.34	15	28
4	1 1/8	4		0.300	0.600	0.800	0.900	1.1	18	0.45	15	40
10	1 1/8	4		0.390	0.780	1.0	1.1	1.4	18	0.58	15	28
9	2 1/8	4	5	0.580	1.1	1.5	1.7	2.1	18	0.87	15	28
5	2 1/8	5		0.60	1.2	1.6	1.8	2.2	18	0.90	15	40
11	2 1/8	5		0.78	1.6	2.1	2.3	2.8	18	1.2	15	28
12	3 1/8	5	6	0.90	1.8	2.4	2.7	3.3	18	1.4	15	28
13	4 1/8	5	7	1.1	2.2	2.9	3.3	4.0	18	1.7	15	28
6	3 1/8	6		1.2	2.4	3.2	3.6	4.3	16	1.8	12	40
14	3 1/8	6		1.5	3.1	4.1	4.6	5.8	16	2.4	12	28
15	4 1/8	6	7	1.8	3.5	4.6	5.2	6.5	16	2.7	12	28
16	4 1/8	6	7	1.9	3.8	5.0	5.6	7.0	16	2.9	12	24
7	4 1/8	7		2.0	4.0	5.3	6.0	7.5	14	3.1	12	40
18	4 1/8	7		2.6	5.2	6.9	7.8	9.7	14	4.0	12	28
17	5 1/8	6	6	2.7	5.4	7.2	8.1	10.0	16	4.1	12	28
19	4 1/8	7	6	3.7	7.4	9.8	11.0	13.3	14	5.7	12	28
8	4 1/8	7	8	5.0	10.0	13.0	15.0	18.0	14	7.5	12	28

Center bolt sizes: plates numbers 1, 2, 3, 20, 21—numbers 8–32; plates numbers 4, 9, 10—numbers 10–32; Plates numbers 5 to 19—3/16–18.

shown in Table II. Because of the absence of the alternating current in these applications the plates are rated slightly higher than for rectifier applications.

FORWARD AND REVERSE RESISTANCE CHARACTERISTICS

The forward and reverse resistance characteristics are very important in a rectifier. An ideal rectifier would be one with zero resistance in the forward direction and infinite resistance in the reverse direction.

Since selenium rectifiers do not meet these requirements, their effects on the circuits with which they are to be used must be considered. The forward resistance is not fixed or linear. At very low voltage and current the resistance is very high (see Figures 5 and 6). As the voltage and current are increased, the resistance decreases very rapidly, up to approximately 20 per cent of plate rating. From 20 to 140 per cent the forward resistance changes only a small amount. From this we would expect to have the greatest amount of regulation take place in a rectifier in the first 20 per cent of normal load. This is true, and it must be considered in rectifier applications where regulation is important. This nonlinear resistance characteristic, which at first seems to be undesirable, makes possible good rectifier regulation and suggests the possibility of their use as direct-voltage regulators.

The reverse resistance performs somewhat the same way as the forward but is not as critical. Generally, applications demand maintenance of high reverse resistance at all times. At the critical voltage in the reverse direction the resistance decreases very rapidly, and care must be taken to avoid overheating and rupture of the barrier layer at this point. Plates must not be operated at voltages above rated values.

VOLTAGE REGULATORS

In d-c applications selenium rectifiers can be operated on the steep portion of the resistance curve (Figure 6), and the rectifier plates can be used as regulators. If the plates are operated in the forward direction at about 0.70 volt per plate, the effect of a variable regulating resistance across a load can be achieved. This, coupled with the necessary voltage-dropping resistances, will provide fairly good regulation. See circuit in Figure 16.

As the voltage across the load increases, the resistance of the rectifier plates decreases rapidly, permitting more current to pass through the rectifier and creating greater voltage drop across R, thereby regulating voltage across the load.

Because of the very nature of the resistance characteristics, it is difficult to predetermine the exact combinations of plates for any one application. It is, therefore, desirable and most generally necessary to make actual tests for individual problems.

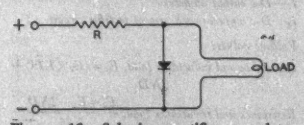

Figure 16. Selenium-rectifier regulator circuit

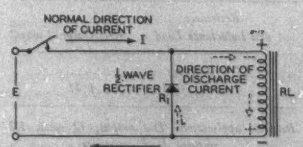

Figure 17. Selenium-rectifier arc-suppresser circuit

The curve in Figure 6 cannot be taken for all problems, since the complications which arise in each circuit are different, and one curve could not apply to all applications. Production tolerances for rectifier plates cannot be used in this type of service. In practically all applications it is necessary to select plates and match them for the particular project. The curve in Figure 6 was taken from a series of single plates.

In applying the selenium rectifier to these regulator circuits, the amount of current that will flow through the plates at maximum-voltage condition must be considered. If this current is too high for the size of plate, additional series plates must be added. It may not be possible to increase the surface area without increasing the number of series junctions, as this might unbalance the regulation circuit because of the increase in shunt current through the rectifier.

CIRCUIT ELEMENTS

The nonlinear resistance characteristic is also desirable in network circuits where small voltage changes cause great resistance changes. Selenium rectifiers are working successfully in such applications. These are difficult problems, and particular care must be used to insure proper operation. By special stabilizing of the plate and matching of it to the circuit, balanced operation usually is assured. If rectifiers that are not stabilized and matched are left idle, they may become unbalanced. In rectifier applications this unbalance may occur during long idle periods. Balance is restored, however, as soon as full voltage and load are applied and normal operation takes place without any unbalance indication. In circuit networks, however, full voltage and current generally are not applied, and the recti-

fier would remain unbalanced. Hence, stabilizing and matching plates for this type of service are important.

ARC SUPPRESSION

Half-wave rectifiers may be used across inductive circuits carrying direct current to suppress arcing across contacts and to limit voltage surges. The rectifier is connected across the inductance, matching the polarity of the power supply as shown in Figure 17. Thus, the rectifier offers a high resistance to the applied voltage and a low resistance to the surge current generated by the collapse of the field in the inductive load.

The electromotive force generated in the coil at the instant the applied voltage source is broken is

$$e_b = E\frac{R+R_1}{R} \qquad (1)^7$$

The current, i, generated in the coil at any time, t, is

$$i = \frac{I}{\epsilon^{\frac{(R+R_1)t}{L}}} \qquad (2)^7$$

e_b = voltage generated with collapse of field
E = applied voltage
R = resistance of coil
R_1 = forward resistance of rectifier
i = induced current flowing in forward direction through R_1 at time t
T = time in seconds
L = inductance in henrys
$\epsilon = 2.718$

In formula (1) the induced voltage varies in the ratio $\frac{R+R_1}{R}$. Then, if R_1 approaches infinity, when the switch is opened, e_b rises and high voltages are generated. This condition exists when the contact points are opened to break the current. The air gap between the opening contacts becomes ionized and arcing occurs. This arcing, from the discharge of an inductive load, will shorten considerably the life of contacts, and the application of the proper selenium rectifier will reduce this condition to a minimum.

From formula (2) it can be seen that the current i at any time t varies with the resistance R_1 of the external load. The maximum possible current which can be induced by the coil will occur when $R_1 = 0$, and $t = 0$. By substitution in formula (2) it will be found that i is then equal to I, the steady-rate direct current.

In choosing a rectifier to serve as an arc quencher there are two conditions which must be met. First the rectifier must be able to block safely the steady direct voltage; second, it must be able to carry the current without overheating. The largest current a spark-quenching rectifier will be required to carry is the steady-state direct current in the circuit. This condition will be found where the number of discharges per second is high. When the rate of discharge is decreased, the size of the rectifier may be decreased. It should be remembered that the ambient temperature must be taken into account in this application, as well as for all other applications of selenium rectifiers.

SURGE VOLTAGES AND CURRENTS

Although excessive voltage or current are always undesirable and often cause damage to a dry-plate rectifier, selenium rectifiers will withstand high overvoltage and current for short duration.

For durations of 20 to 30 microseconds, tests show that back voltages as high as 140 to 250 volts may be applied without breakdown. This means that the maximum safe voltage would be somewhere below 140 volts. These tests do not mean necessarily that we should design for such overvoltages. This ability to stand overvoltage is helpful only in case of emergency voltage surges such as may be caused by lightning discharges.

Surge currents in the forward direction may exceed the normal rating by 30 to 50 times for durations of 20 to 30 microseconds under good contact conditions between front electrode and the contactor plate.

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The Centenary of the Morse Telegraph

H. W. BIBBER
MEMBER AIEE

THE MAGNITUDE of the telegraph industry, its effect on daily life, the stimulus it has given to scientific enquiry and electrical engineering, and especially the influence it had on the formation of the AIEE, all combine to make it fitting that our Institute do Morse and his associates honor on the 100th anniversary of their first public telegraph line between Baltimore, Md., and Washington, D. C. A session in recognition of the occasion was held during the 1944 AIEE summer technical meeting.[1–8]

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To some of our younger members, it may be news that of the 25 men who signed the original organization "call" for the AIEE published in the April 15, 1884, issue of *The Operator* (the leading American electrical journal of that time), 21 were in the telegraph business. The first president of the Institute was Norvin Green, president of the Western Union Telegraph Company. Two of the initial vice-presidents and four of the initial managers were in the telegraph industry. In succeeding years telegraph men continued to exercise influence in shaping the destiny of the Institute, and today they form a valued group of our membership.

In keeping this centenary we do not commemorate the first working telegraph in the world, as it appears that a line 13 miles in length from Paddington Station to West Drayton on the Great Western Railway in England was put into operation in 1838. This was constructed on Professor Charles Wheatstone's scheme employing six wires and five needles, wherein two converging needles were made to point to letters on a dial. We do not observe the anniversary of the invention of audible electromagnetic signaling at a distance, for Joseph Henry demonstrated to his students at the Albany Academy, Albany, N. Y., in 1832, the ringing of a bell by electromagnetic action through a circuit of a mile of wire. Nor do we celebrate the passage of a century since Morse first demonstrated publicly the

practicability of his invention. Successful operation was shown by Morse (through ten miles of wire) in New York City at New York University in January 1838, in Philadelphia before a committee of the Franklin Institute the same month, and in Washington in February of that year before the House committee of commerce.

Rather do we celebrate the persistence of Morse and his associates in overcoming the obstacles they found in their path due both to Nature and to man. From the year 1844 the development of the telegraph industry in the United States was spectacular. Through the extension of telegraph lines to all parts of the country there came to be aroused an interest in this new force or power, electricity, and many electrical inventors in other fields began in telegraphy.

The transmission of a telegraph message between Baltimore and Washington in 1844 introduced a new era in communication and in the practical application of electricity and perhaps led indirectly to the founding of the AIEE. The early struggles and discouragements of the artist-turned-inventor Samuel Finley Breese Morse, at last crowned by success, are an exemplary chapter in American life.

EARLY DEVELOPMENTS IN TELEGRAPHY

It is not appropriate in this paper to review in detail the experiments previous to Morse's in which electricity had been tried as a means of communicating intelligence. These attempts were very numerous; indeed a volume of several hundred pages by J. J. Fahie is entitled "A History of Electric Telegraphy to the Year 1837." Suffice to say that frictional electricity had been used for signaling over a distance of some thousands of feet nearly 100 years before 1844, and that experiments employing dynamic electricity with chemical receiving indicators had started soon after Volta's invention of the "pile" in 1800. Oersted's discovery in 1820 of the effect of the electric current in a wire on a neighboring compass needle led to the development of needle telegraphs by several European inventors in the following years.

This brings us to Samuel Finley Breese Morse. What sort of man was he and how did he become interested in the electromagnetic telegraph?

Born in Charlestown, Mass., in 1791, the son of a militant orthodox clergyman who was one of the distinguished promoters of a knowledge of geography, he was raised in an intellectual atmosphere that must have been stimulating to say the least. By the time he was 14 he had completed the preparatory studies at Phillips Andover Academy for Yale College and entered there. His self-taught skill in art developed to the point where during his senior year he was able to charge five dollars for miniatures painted on ivory. Indeed, as his college work came to a close, his interest in art exceeded his interest in any academic studies, even in natural philosophy, where he was first introduced to electricity by Professor Silliman.

He persuaded his father to send him to England in 1811 to study art, which he did with seriousness of purpose and success. As he left England to return to the United States in 1815, he felt that his real interest lay in painting historical scenes which he felt required more imagination and were more intellectual than portraits. Ironically enough, when he started out to earn his living as a painter in New England and soon afterward in South Carolina, he found that he could get commissions for nothing but portraits, and these in none too great quantity. In the intervals between portrait commissions he turned to other interests, showing his extraordinary versatility. He and his brother were the patentees of a water pump, and he worked diligently for a time on a marble-cutting machine to make easier the carving of statues of this stone. On going to live in New York he helped to found and became president of the National Academy of the Arts of Design. He attended Professor Dana's lectures on electromagnetism given at Columbia College. In his early years in New York he helped found the Journal of Commerce, a paper that has had a long career. He was often in straitened financial circumstances.

With the promise of sufficient financial backing to make possible his return to England, and a tour of Europe in the interests of art, he left New York in November 1829 and spent the next three years on the continent. While in France he noted in his letters the use of the Chappe semaphore telegraph devised during the French Revolution, and commented on its advantages and limitations.

It was on his return from Europe in 1832 on board the sailing ship *Sully* that the idea of an electromagnetic telegraph seems to have occurred to him. Morse later described the circumstances as he remembered them. At the lunch table about the middle of the trip, Doctor C. T. Jackson of Boston who was as much interested in "natural philosophy" as in medicine, was discussing the recent experiments by Ampère with Sturgeon's electromagnet. On being asked whether the flow of electricity was not retarded by the length of the wire, he replied that electricity appeared to pass instantly over several miles of wire. Morse then said, "If this be so, and the presence of electricity can be made visible in any desired part of the circuit, I see no reason why intelligence might not be instantaneously transmitted by electricity to any distance." Morse then left the group and pondered ways in which a practical instrument could be constructed, making sketches of his thoughts in a notebook in which he recorded sketches and ideas for paintings.

His first idea of sending intelligence was to use an electromagnetically actuated stylus to mark a moving strip of paper with dots and dashes appropriately spaced. The dots and dashes were to represent numbers, which would be used to identify numbered words in a dictionary. The proper arrangement of dots, dashes, and spaces between was to be secured by setting type bars with appropriate faces of dots and dashes in a "port rule" and running these at constant speed under a button attached to a key in such a way that the circuit was opened and closed to correspond to the projections and depressions of the line of type.

On his return to New York he found the same financial difficulties which had dogged his steps before, and he returned to painting as a livelihood and to politics as an avocation. He was appointed professor of sculpture and painting in the newly formed University of the City of New York in 1832, but he received no salary except fees from his students and was not required to give any lectures. In 1835 he was given a new title in New York University, professor of the literature of the arts of design; assigned some regular lectures; and granted the free use of a large room in the then new Washington Square building.

In the fall of that year he showed a working model of his telegraph to friends, and in January 1836 a professor of science at the university, Leonard D. Gale, visited Morse's rooms and saw his telegraph. This was the original model in which a pencil was moved transversely on a continuously moving paper tape. Painting took most of his time, however, and it was not until 1837 that the report of a new French telegraph stimulated him to renewed effort on his own. He realized that he needed scientific help, and enlisted Professor Gale as a partner in the enterprise. The latter's immediate contribution came from his knowledge of a paper of Joseph Henry's dealing with improvements in electromagnets. Gale suggested that instead of a few turns of wire wrapped around each leg of a horseshoe receiving magnet fed by a "quantity" battery, Morse had better employ a large number of turns and use an "intensity" battery. The improvement in operation was marked. Where difficulty had been experienced in sending messages through a hundred feet of wire, it became possible by November 1837 to operate the instrument through ten miles of wire.

The telegraph relay, an essential element of the Morse system, was already in Morse's mind in 1836, according to Gale's later testimony, and a definite workable design was shown to Gale in 1837. It

appears that Joseph Henry invented the relay earlier, but as it had not been described in anything Morse had read, nor did Morse make Henry's acquaintance until late in 1837, it was evidently an independent invention by Morse. He originally conceived of its use as a one-way repeater, believing that electromagnetic action could not take place over too many miles without being "renewed" by the action of another battery.

IMPROVEMENT OF THE TELEGRAPH

The House of Representatives in February 1837 had passed a resolution directing the Secretary of the Treasury to investigate the feasibility of setting up a "system of telegraphs for the United States." In March 1837 a circular of inquiry was issued by the Secretary, and Morse was further stimulated to every effort to improve his invention. Thus it was that he was ready to welcome the efforts of Alfred Vail who offered mechanical skill that Morse did not possess, and financial support for the enterprise through his brother and father.

Young Vail had graduated at New York University in 1836 intending to go on with study of theology in preparation for the Presbyterian ministry, but the chance visit to Professor Morse which he made in the early autumn of 1837 changed the course of his career. His father was the fairly prosperous proprietor of the Speedwell Iron Works in New Jersey, where Alfred had received an apprenticeship in the mechanic arts. Alfred felt certain that he could persuade his father and brother to support the telegraph enterprise in his name. It seemed to him that here was an undertaking into which he could put his heart. He and Morse then entered into a contract on September 23, 1837, whereby Vail undertook to construct at his own expense one of the telegraphs of Morse's design to be exhibited before Congress, and to pay the costs of the exhibition and United States patents. In return Vail was to receive one-fourth of all rights in the invention in the United States, and a share in any foreign patents which he might furnish the means to obtain.

Morse completed a caveat for his patent on October 3, 1837. In it he claimed:

1. A system of signs by which numbers are signified.

2. A set of type adapted to communicate the signs.

3. An apparatus for regulating the movement of the type so that the electric circuit may be made and broken in accordance with the moving type.

4. A register for recording the signs at the receiving end.

5. A dictionary or vocabulary with each word numbered.

6. Modes of laying the conductors to preserve them from injury.

Looking back on the work of Morse, his predecessors, and his contemporaries, it can be asserted that his was the first *recording* electromagnetic telegraph. The elements of his device were all known at the time. He made no new basic discovery, but he made a new combination of the known elements.

It is to Vail that credit appears to be due for changing the relative position of the magnet and armature so that a vertical motion of the marking stylus was achieved, making possible the registration of real dots and dashes.

With the improved recorder and a new battery built by Professor Gale, the telegraph was exhibited publicly to the people of Morristown, N. J., on January 10 and 11, 1838, with operation over three miles of wire. On January 23 it was shown to hundreds of people in New York with the new alphabetic code which did away with the numbered dictionary, then to a committee of the Franklin Institute at Philadelphia, and at last shown in the committee room of the House committee on commerce to that group itself and to large numbers of interested Congressmen. The demonstration was a complete success and the chairman of the committee was instructed to report an appropriation bill for $30,000 to construct an experimental line from Baltimore to Washington.

In the course of the demonstration to the committee, its chairman, F. O. J. Smith of Maine, had become enthusiastic about its money-making possibilities as a private enterprise and wanted to become a partner. The existing partners, Morse, Vail, and Gale, felt the need of an aggressive assistant in promoting the telegraph on the political and economic side, and so Smith was taken in. This event was the occasion for a formal statement among the partners as to their relative shares of ownership: Morse, 9; Smith, 4; Vail, 2; Gale, 1. Vail and Morse had reduced their interest in order to take Smith in, to get the value of his legal services and aggressive disposition.

Samuel F. B. Morse

Morse and Smith left for Europe in the spring of 1838 with the hope of obtaining foreign patents on Morse's invention. Disappointment came in England where the Attorney General ruled that previous publication debarred Morse from obtaining a patent, in France where the dilatory procedures of government wore him out, and in Russia where the Czar finally decided that he did not want telegraphic communication after all. The bill reported to Congress from Smith's commerce committee did not reach a second reading, so hard was it to get the members of the House to realize that this was more than a fascinating toy.

Morse returned discouraged in 1839 and passed through a very troubled period. His patent was issued on June 20, 1840. But the financial depression that started in 1837 had enveloped the whole country and even the Vails had no further funds to expend in promoting the telegraph. Smith had experienced financial reverses. Morse now came into prominence and secured needed finances as a daguerreotypist, even teaching the art to others for a fee. Though he practiced steadily for little more than two years, he earned considerable fame.

In October 1842 he laid a wire coated with pitch from New York's Battery to Governor's Island and until it was caught by a boat's anchor it provided successful communication under water. It was not the first submarine telegraph in the world, but the first in America.

BUILDING OF THE FIRST LINES

During the autumn he again memorialized Congress and, at the risk of becoming penniless, put on a more striking demonstration than ever between two rooms of the Capitol. A new appropriation bill of $30,000 was reported by the commerce committee, but compared to other legislation it lacked priority. The end of the session March 3, 1843, approached. The telegraph-appropriation bill passed the House on February 21 and it seemed as if the jammed Senate calendar could not possibly permit of its passage. But after Morse had given up hope on March 3, so the legend goes, as evening approached, and he had returned deeply discouraged to his hotel, his bill was passed and signed by President Tyler. The young lady who called at his hotel the next morning to inform him of the great news was Annie Ellsworth, daughter of the Commissioner of Patents. To her, a little more than a year later, Morse gave the privilege of composing the first message to be sent over the completed line.

With the Congressional appropriation granted, Morse proceeded to plan on laying the lines underground, insulated in lead pipe two feet below the surface. As the available money would not permit

purchasing land for a right of way, application was made to the Baltimore and Ohio Railway for permission to bury the telegraph wires along its line between Baltimore and Washington. The granting of permission constituted the start of a cooperation between the railway and the telegraph that has existed ever since. A contract was let for furnishing the lead pipe with insulated wires inside.

The trenching contract was placed with F. O. J. Smith for disposition. Into his office in Portland, Me., there came one day in 1843 a young plow salesman, Ezra Cornell, of Ithaca, N. Y., who was later to found the university which bears his name. At Smith's request, Cornell invented a combined plow, cable-reel, and filler-in drawn by oxen which successfully laid the lead-pipe cable at a rapid rate compared to hand trench digging. The cable was being laid faster than the maker could supply it. Then, after nine miles were in the ground, tests showed that the insulation had failed. The newspapers were following the enterprise closely, and Morse could ill afford a failure of his scheme now. He arranged with Cornell to contrive a breakage of the special plowing machine so that time could be secured for tests and experiments with other manufacturers' pipe, and other methods of insulation. The experiments were all disappointing. It was a period of deep discouragement, as much of the original $30,000 now had been spent. But Vail read in an English journal of the success which Wheatstone and Cooke had attained with wires placed overhead on poles after underground lead-pipe cable had failed.

Morse decided that this was the answer to the problem, and in February 1844 work was started on a pole line along the railroad right-of-way. Smith in the meantime had become a disturbing element in the enterprise, and he and Morse became life-long enemies. During the stringing of wires on the pole line tests were made frequently to make sure that all was well this time. In the course of these Alfred Vail discarded the "port rule" and type mechanism by which the code letters were sent, and found Morse could read the receiving tape just as well when he opened and closed the circuit by hand. Thus was the telegraph key invented.

The first formal message sent over the completed line composed by Miss Annie Ellsworth, "What hath God wrought," was considered prophetic by Morse who had high visions of the public service which could be rendered by the telegraph. To keep the potential power of the telegraph for the public good, Morse was anxious to have the government buy the patent and issue regulated licenses to private parties to construct lines, and as well to build lines for its own business. But Congress was now preoccupied with the Mexican troubles, and so it was left for private enterprise to develop the new mode of communication, as soon happened.

Of the original group of partners, Morse, Vail, and Smith continued active in the telegraph business. Cornell, who had come into the enterprise at the building of the Washington–Baltimore line, also followed along in the industry. He played a large part in the founding of the Western Union Company; he was a director for 15 years, and the largest stockholder for 20 years.

SIGNIFICANTS OF THE TELEGRAPH

In retrospect, what lessons can be drawn from the work of Morse and his associates? The most evident is that indomitable persistence is necessary to convince men of the possible utility of new technical devices, and that what looks like the most serious difficulty of a series offered by nature may be the last that has to be overcome. Co-operative effort was what made the telegraph a technical success, and had Smith been of different character, co-operation would have hastened its acceptance by Congress and the country. The pure scientists, Joseph Henry in particular, played a significant part. The prompt publication of scientific discoveries and technical improvements aids material progress; Henry's paper on the electromagnet and the report of Wheatstone's use of overhead lines are striking examples.

It is interesting to note that three features which Morse tried out on the Baltimore–Washington line but which were later discarded, have returned to use in recent years:

1. A moving paper tape on which the message is recorded.
2. Mechanical rather than manual sending of the code impulses.
3. Laying telephone and telegraph lines underground by means of a plow similar to that devised by Ezra Cornell.

Turning now to the material development of the telegraph industry in the United States, what does the passage of 100 years show? In 1844 there were two public telegraph stations and a single line connecting them. In 1944 there were 33,000 public message offices; in addition there were agency stations by which 90,000 places could be reached. Used in public message and related services were 2,300,000 wire miles.

There seems to be no record available of the number of public messages sent from May 24, 1844, to the end of that year, but in the year previous to January 1, 1944, some 206,000,000 public messages were handled. Yet the preceding figures do not show completely the development of telegraphy in the United States because of the large number of private-line stations, 20,000 at the beginning of 1944, which were served by 1,750,000 circuit miles of line. Many more installations that are telegraphic in nature are represented by the 16,000 teletypewriter (*TWX*) installations and the 2,000,000 circuit miles which provide for their interconnection. The magnitude of the traffic on this *TWX* system may be judged from the fact that in the year 1943 more than 14,500,000 service connections were made, on each of which several messages may have passed.

After observing that "It was perhaps no accident that the telegraph in its most practical and successful form was invented, not by a physicist who had spent years in the study of electricity, but by an artist," R. T. Barrett goes on to say, "The genius of the great artist consists less in creating things than in combining familiar things in new relations. Fundamentally he is guided by rules with which all painters are familiar. When he surpasses his fellows, he does so in the skill with which he seizes upon commonplace things and unites them into creations of consummate beauty. It may have been the artist in Morse that led him to see, in what other men had produced in the field of electrical research, the separate elements of the telegraph; that enabled him to visualize them in new relationships."

In the life and work of Morse we can identify several features of the "American spirit" characteristic of our 19th century, which has been described so clearly by Dixon Ryan Fox in an address before the Newcomen Society. Morse showed in but few instances anything but a self-disciplined decency and concern for truth. He had a basic respect for hard work, and as a speculator in both art and telegraphy he was prepared to weight the balance with his sweat in the same way as the pioneer farmers of the West.

He was a combination of inventor and promoter, of whom the United States was fortunate in having several in the last century. Typical of many of his time he seems to have had a personal philosophy that was a blend of idealism and materialism, with the latter strain tending toward dominance. He is an outstanding example of the opportunity which America, in contrast to Europe, offered to a man to rise, fall, rise, fail, and rise again. His ultimate success showed that this was a land of opportunity, not only for young men—and let us remember that Morse was 53 years old in 1844—but for older men as well.

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Electrically Heated Homes in the Tennessee Valley

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THE USE of electricity for house heating is not new. As early as 1914, homes in the Northwest were being heated by electricity. It is estimated that by 1920 there were over 2,000 homes in Tacoma, Wash., using this means of heat. For a few years prior to the war, the use of electric heating spread rather rapidly on the west coast, particularly in central California.

The use of electricity as the main source of heat in homes located in the Tennessee Valley area began about 1935. It is estimated that today there are approximately 1,000 electrically heated homes in the valley. These are scattered quite widely throughout Tennessee and the northern parts of Alabama and Mississippi.

Public acceptance of this type of heating is now quite well established in this section. The experiences of those using electric heating have proved its many advantages, among which are cleanliness, elimination of fuel storage and waste removal, quick availability for sudden cool spells or to drive off the chill of an early fall or late spring evening. This form of heat offers an almost ideal means of maintaining heating comfort in the home. During the two years before the war curtailed general home building, there were quite a few new homes provided with electric-heating installations. Recent inquiries indicate that there exists a keen interest in heating homes electrically. At least four investment builders have expressed their intention of building several new "all-electric" homes, including electric heating, as soon as materials again become available.

INTEREST IN ELECTRIC HOUSE HEATING GROWING

In the Tennessee Valley region electricity is distributed to the consumer through municipalities and rural electric co-operatives which in turn purchase it from the Tennessee Valley Authority. The areas served by these systems vary widely in extent and number of customers; therefore, the problems of house-heating loads are not the same for all of them.

The growing interest in electric house heating has stimulated much discussion concerning the effect of this type of load on distribution systems. A number of pertinent questions has been raised regarding the amount of energy required and the cost of heating homes of different sizes and types of construction, the load demands of a heating installation, and the time of day when these occur.

Essential substance of a conference paper presented at the AIEE summer technical meeting, St. Louis, Mo., June 29, 1944.

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The growing interest in electric house heating has stimulated much discussion concerning the amount of energy required and the cost of heating homes of different sizes and types of construction, the load demands of a heating installation, and the effect of this type of load on a distribution system. Data collected by the Tennessee Valley Authority and analyzed in this article help to answer some of these questions.

In order to help answer some of these questions, the Tennessee Valley Authority has collected considerable data on the operation of various heated homes located throughout the region and has made some analyses of these data in order to determine:

1. How this form of heat is accepted by the consumer from the standpoint of service and cost.
2. The amount of energy used for heating in well-insulated houses as compared with the amount required for heating uninsulated houses.
3. The load characteristics of electric house heating and its effect on the power demands of the distributor.
4. The value of this type load as a potential source of revenue.

It should be noted that this study is somewhat limited in scope. There are some factors which we have not been able to analyze up to the present time. Through extensive co-operation of various power distributors data on a number of typical electrically heated homes have been collected. These include information on the size of house, type of construction, family occupancy, heating installation, number of kilowatt-hours used, and load-demand records.

MANY FACTORS AFFECT HEAT REQUIREMENTS

Regardless of the method employed to provide heat in a house, certain basic principles must be observed. These have to do with the heat requirements and heat losses of the structure itself. Various materials and combinations of materials are employed in the construction of houses. The rate of heat transfer through walls, ceilings, and floors has been the subject of extensive laboratory tests; and data are available from a number of reliable sources by which the theoretical heat losses from any building can be computed. The actual amount of heat used in a given home, however, may vary quite widely from such theoretical quantities, because of different conditions of occupancy. The room temperatures maintained have been found to vary widely among different families. In some homes, occupied only by a husband and wife, with both working, little heat is used except in the evenings, while in other homes where there are small children or elderly persons, high temperatures are maintained throughout the day. Many families are careless about keeping outside doors closed, and often larger children pass into and out of the house frequently. These factors often affect quite substantially the amount of

Table I. Analysis of Electric-Heating Data Collected From 30 Residences of Various Sizes

Averages Per House in Size Groups

Number of Rooms	Volume (Cu Ft)	Connected Load (Kw)		Annual Kwhr		Annual Revenue	
		Total	Heating	Total	Heating	Total	Heating
4	6,240	28.79	13.98	14,848	9,314	$126.80	$ 48.50
5	7,500	31.00	16.50	16,910	10,186	134.84	52.14
6	11,780	37.60	23.00	22,399	15,551	174.78	89.58
9	11,922	50.50	32.90	23,751	17,763	184.39	105.07
Average per house	8,930	34.28	19.48	18,278	12,052	147.07	65.98
Average per room	1,685		3.67		2,274		12.40
Average per cubic foot			2.18 watts		1.35		0.0074

The group of 30 residences from which the above averages were derived consisted of ten each of the four- and five-room houses and five each of the six- and nine-room houses.

heat used. Irregular habits of living, absence from home, and differences in retiring time also have their effects on the heat requirements of a home. Often these have more influence on the amounts of energy used than the differences in degree-days.

The Tennessee Valley lies within a region which has moderate climate. The normal winters average about 3,200 degree-days. The degree-day is a unit based upon the temperature difference in Fahrenheit degrees between the mean temperature of the outside air over a 24-hour period and 65 degrees Fahrenheit. The mean temperature is the average of the maximum and the minimum temperatures of the period. In the southern portions of the area the normal heating season is 2,500 degree-days, and along the northern boundary a normal winter has around 4,000 degree-days.

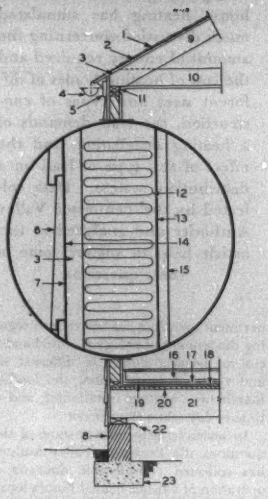
THE MAJORITY OF HOUSES ARE SMALL

The application of electric heating has been confined almost wholly to what might be termed small homes. Such a home, typical of the majority, has a volume of heated space between 6,000 and 9,000 cubic feet. A few are as large as 12,000 cubic feet. A small four-room well-insulated house (Figure 1) will have a heat loss of about 35,000 Btu per hour based on a temperature difference of 70 degrees between the outside air and room temperature. This is 500 Btu per hour for each degree difference. The theoretical heating load for a 30-degree day, therefore, would be 15,000 Btu per hour, or 106 kilowatt-hours for a 24-hour day. With a heating season having 3,500 degree-days, such a house would require 12,600 kilowatt-hours. This is predicated on the assumption that all parts of the house would be heated to the same temperature all the time. In practice, however, this is never the case. Usually bedrooms are not heated to a temperature so high as that required for comfort in the other parts of the house. Much of the time no heat is used in the bedrooms. This practice results in less heat actually being used than the computed quantities.

THE AMOUNTS OF ENERGY USED

The average amount of energy estimated as being used for heating is shown in Figure 2. In ten four-room houses on which data were collected the average is 9,300 kilowatt-hours per heating season. This quantity was calculated from the records giving the amounts of energy actually used and taking the number of kilowatt-hours used during the summer months as a base from which the amount of energy used for nonheating purposes was calculated. The average amount of energy used for heating in a group of ten five-room houses is 10,200 kilowatt-hours. In five six-room houses the average was 15,500 kilowatt-hours per season and for the same number of nine-room houses

A. Typical small house designed for electric heating



B. Wall section of house

1—Roof	*13—Moisture barrier*
2—Felt	*14—Insulation, 0.06 coefficient*
3—Sheathing	*15—Plaster or plaster board*
4—Gutter	*16—Base*
5—Cornice	*17—Finished floor*
6—Siding or veneer	*18—Insulation board*
7—Resin paper	*19—Building paper*
8—Foundation	*20—Subfloor*
9—Rafter	*21—Joists*
10—Joist	*22—Termite strip*
11—Metal angle	*23—Footing*
12—Insulation	

Figure 1

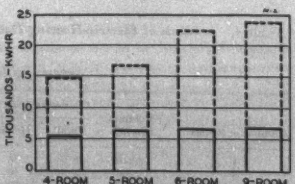


Figure 2. Kilowatt-hours used per year for heating and for other purposes in homes of various sizes

Dotted line—Heating
Solid line—Other uses

17,760 kilowatt-hours. The average for the 30 houses is 1.35 kilowatt-hours per cubic foot per season at a cost of 7.4 mills per cubic foot on the standard TVA residential rate. Additional data by house groups are shown in Table I. Further analysis of the data pertaining to the heat requirements of well-insulated houses as compared to those having poor or no insulation indicates that the energy required for heating a well-insulated house is from 20 to 35 per cent lower.

The cost of electric heat should not be compared to heating by other means on a "cost-of-fuel" basis alone. Users of electric heat are quick to point out that substantial savings in cleaning and redecorating result where this method of heating is used. The total construction cost of the house can be reduced through the elimination of space required for the heating plant, or else this space can be utilized for other purposes. Those who use electric heat praise it very highly.

INDIVIDUAL ROOM HEATERS OF THE RADIANT-CONVECTION TYPE USED

With only a few exceptions the electric-heating installations in the Tennessee Valley area employ individual room heaters of the radiant-convection type. Most of these are controlled automatically by thermostats built into each heater. This method of control provides for different temperature levels in various parts of the house. From the standpoint of the power distributor this has the advantage of improving the diversity of the load on the distribution system. The installation cost of these heating systems, including heaters, wiring, and prorated additions to the service and metering equipment averages about $25 per kilowatt.

In a six-room house, usually the total heating load will be divided among seven or eight units which are located in the various rooms. Except during a warming-up period, it is very seldom that all of these heaters will operate simultaneously. This results in improving the load diversity both in individual houses and in a group of houses.

TOTAL DEMAND IMPORTANT TO UTILITY

Inasmuch as it is the complete load and not the heating load alone which must be served by the power distributor, the total demand of any individual house or group of houses becomes of extreme importance. In order to arrive at some idea of the character of a daily load curve on "all-electric" homes having heating installations in addition to cooking, water heating, refrigeration, lighting, and miscellaneous appliances, recording instruments were installed in a group of six adjacent houses at Knoxville and in several individual houses in Chattanooga. All of these houses are of recent construction, and the electric-heating systems were installed when the houses were being built. The Knoxville group consisted of four four-

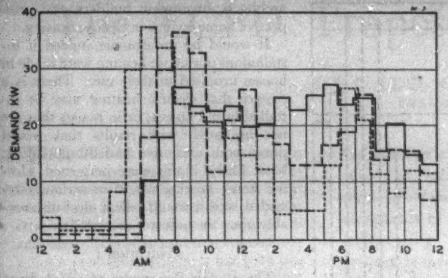


Figure 3. Demands on six electrically heated houses

February 6, 7, and 8, 1942
Solid line—Saturday; 28 degree-days
Dashed line—Sunday; 28 degree-days
Dotted line—Monday; 24 degree-days

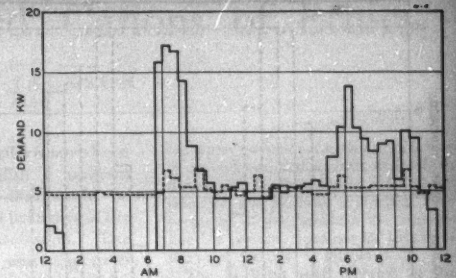


Figure 4. Typical daily load curves on two houses illustrating the effect of different schemes of operation

January 13, 1944; 30 degree-days; mean temperature 35 degrees Fahrenheit

Solid line—All heat off at night
138 kilowatt-hours—maximum demand 17.7 kw
29 per cent load factor 47 per cent demand factor
Dotted line—Part of heaters operated continuously on thermostats
126 kilowatt-hours—maximum demand 6.9 kw
76 per cent load factor 21 per cent demand factor

room and two five-room houses extremely well-insulated. The radiant-convection heaters are flush type installed in the outside walls, and the heating load totaled 70 kw for the six houses. In each house there were installed a range, water heater, and refrigerator in addition to lighting and miscellaneous appliances. The total connected load of the six houses was 162 kw, an average of 27 kw per house. The average total annual energy used for all purposes over a two-year period was 67,347 kilowatt-hours, or 11,224 kilowatt-hours per house. The portion of energy estimated as being used for heating was 42,279 kilowatt-hours, or 7,046 kilowatt-hours per house, which is 63 per cent of the total.

This group of six houses having a total connected load of 162 kw is being served satisfactorily by one 50-kva transformer. There are 52 houses in this one subdivision, all with electric heat. Each house is served through a 50-ampere 240-volt three-wire self-contained meter and a 100-ampere service switch. The circuits for the heaters are 230-volt and are run with number-12 conductor to the small units and number-10 conductor to the large units. The load is divided among eight transformers. These are arranged as indicated in Table II.

Demand readings were taken of group 2 for several days during the month of February 1942. These readings for three days are shown in Figure 4. The maximum 30-minute demand recorded during this test was 49.5 kw. This occurred between 8 and 8:30 a.m. The outside temperature at the time was 36 degrees Fahrenheit. The maximum hourly demand was 37.5 kw which occurred between 6 and 7 a.m., when the outside temperature was 28 degrees Fahrenheit. During a previous check made in January, a maximum 30-minute demand of 57.5 kw was recorded. At the time of this peak, the outdoor temperature was ten degrees Fahrenheit. The daily load curves shown are typical for this group. Similar data were obtained for several individual houses at Chattanooga. Typical load curves of two methods of operating the heating equipment are shown in Figure 5.

A six-room house having a total load of 37.5 kw with 23.0 in heating established a 30-minute demand of 17.7 kw January 13, 1944. The peak hourly demand was 17.5 kw. This peak occurred between 7 and 7:30 a.m. with an outdoor temperature of 31 degrees Fahrenheit. These demands were obtained by means of a graphic ammeter which indicated the instantaneous load. On the same day the maximum instantaneous demand reached 19.0 kw and lasted for about ten minutes. The load factor for this day was 29 per cent. An interesting contrast to this curve is one showing demands for the same day of another house located a short distance from the first. The total connected load in this house is 33.0 kw, and the heating load is 19.0 kw. The maximum 30-minute demand recorded for this house on that day was 6.9 kw, which is only 21 per cent of the connected load. The load factor for the 24-hour period was 76 per cent.

Further investigation developed the fact that in this house the family allowed the heaters in the living room and a hall to operate throughout the night, while in the other house all heaters were switched off when the family retired and turned on again next morning. The benefit to the power distributor of the all-night operation is obvious.

GOOD DIVERSITY OBTAINED

By selecting from a number of typical daily load curves showing hourly demands recorded when the degree-day requirements were approximately the same, a composite curve of ten houses was prepared. The maximum demand per house was found to be 6.6 kw or 21.7 per cent of the total average connected load. The period when the highest demands came falls between the hours 6 and 9 a.m. A slight increase in load at noon and part of the evening peak between 6 and 7 o'clock most likely are due to cooking operations. The daily load factor for this hypothetical group is fairly high, being 58 per cent.

Table II. Eight Transformers Serving 52 Electrically Heated Houses

Group	Transformer Rating (Kva)	Houses Served
1	50	8
2 (test group)	50	6
3	50	9
4	50	8
5	50	5
6	50	8
7	37	5
8	25	3
Total	362	52

Average per house—6.96 kva.

EFFECT OF HOUSE HEATING ON SYSTEM LOAD CURVES

In order to gain some idea of the effect which house heating may have upon the pattern of a system's load curve, a number of typical winter days was selected, and the hourly demands for distribution systems of various sizes were plotted. Upon these curves were superimposed hypothetical demands representing a house-heating saturation between three and five per cent. It is believed that these are an indication, at least, that while the effect would be somewhat different for each system, in general, there would be no great variations from the existing patterns.

There is, of course, the argument that house heating is a seasonable load and therefore an undesirable one. If one assumes the Knoxville group of houses to be typical, a curve has been prepared showing the number of kilowatt-hours used by months for a period of three years (Figure 6). It is obvious that the major portion of energy used for heating is confined to a period of three or four months.

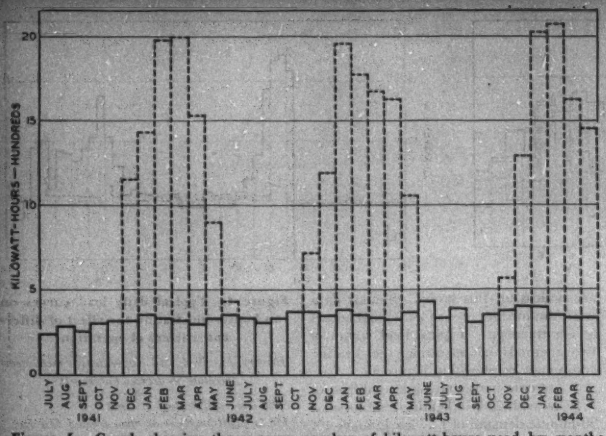

KILOWATT-HOURS — HUNDREDS
20
15
10
5
0
JULY AUG SEPT OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC JAN FEB MAR APR
1941
1942
1943
1944

Figure 5. Graph showing the average number of kilowatt-hours used by months for all purposes in a group of six four-room and five-room well-insulated and electrically heated houses located on Bobwhite Lane, Knoxville, Tenn.

Dotted line—For heating
Solid line—For all other uses

This suggests a need for some type of load which would tend to build up the low use of the summer months. Air conditioning has been suggested as one probable means of doing this. While air-conditioning equipment would not use an amount of energy equal to that required for heating, its general use would help considerably in increasing the number of kilowatt-hours used in July, August, and early September, and in improving the annual load factor.

The use of reversed-cycle refrigeration to provide summer cooling and winter heating has been suggested as a probability. After the war we may see a limited application of the reversed-cycle principle in areas having moderate winters, but there are still some features about it which must be overcome before its use can be sufficiently widespread to make it important in the potential house-heating field. In the meantime a combination of space heaters and room-cooling units may become the first step to all-year air conditioning in the home. There are many indications of a growing interest on the part of architects, investment builders, and prospective home owners in electric heating.

It would be unfortunate indeed if installations of electric heating were made in houses unsuited to their use. There is a danger that electric heating may be installed in old houses, or in houses that are not insulated, with results that would prove both expensive and disappointing. Most likely, if this were permitted, electric house heating would be seriously retarded, and it would reflect most unfavorably upon the industry as a whole.

CONCLUSION

The studies the results of which have been outlined in this article are not complete. It is hoped that much more comprehensive data can be developed when the war emergency is over. There should be more information, for example, on the effects of greater extremes of temperature variation than those encountered in the periods referred to herein. The effects of successive levels of saturation of space-heating installations on the costs of distribution will be a matter of direct interest to utilities and should be studied carefully. Nevertheless, the preliminary results which are already available are important in revealing that the costs to the consumer and the advantages to him of electric heat are such that in some areas it will be a real factor in the load-development picture for the postwar period. While there is a good deal of work still to be done in order to determine the total effect of this load on costs of service, it has been learned that under many conditions there is a high degree of diversity with consequent lowering of the distribution costs. Some distributors of TVA power already have found reason to believe that the space-heating load is a profitable one.

Searchlight Supplements Radio Communication

Specially designed by the Westinghouse Electric and Manufacturing Company to withstand a degree of rough service required of few shipboard lights, this searchlight is here being tested for the intensity of its beam, which should be visible for 17 miles. Mounted on the open decks of United States battleships, cruisers, and destroyers, the signal light substitutes for radio communication to airplanes, shore patrols, and other ships, when radio signals might be intercepted by the enemy or are ineffective because of weather conditions. The glass of the lens, ten times stronger than plate glass, will not shatter under the combined and opposite forces of the heat of the lamp and the cold of icy sea water, nor from the blast of giant guns. The shutters which blink out the messages have been opened and closed a total of 2,000,000 times during testing.

The ECPD Proposed Canons of Ethics

DUGALD C. JACKSON
FELLOW AIEE

For some years efforts have been made to establish a uniform code of ethics that would be acceptable to all branches of the engineering profession. The project is now under sponsorship of Engineers Council for Professional Development; its history and present status are outlined here.

THE TERM "professional ethics" is commonly used quite loosely but, in fact, it means "rules of right conduct in which each item is fundamental to social relations" within the scope of professional activities. It is often said that engineering is not a profession because it has been unable to agree upon a suitable code of ethics which applies through the field of all of our great engineering societies. The lawyers, through the American Bar Association many years ago, adopted a code of ethics which they have modified and added to in the interval and which has 47 items. This code is published by the Association under the title "Canons of Professional Ethics" in a small pamphlet, along with some additional matters relating to judicial ethics. The doctors also, through the American Medical Association, have their code published by the Association in a pamphlet called "Principles of Medical Ethics," containing 42 items. Each lawyer and physician usually possesses a copy of the pamphlet relating to his profession and cherishes it as of importance in his active life.

The engineering societies have never been able to come to such solidarity of views. Most of the important engineering societies possess codes of ethics, but the different codes cover different ground and even where items are similar in content, the phrasecology may be quite different, which makes the whole situation of ethics in the engineering field quite confusing or even chaotic.

Several years ago officers of two of the Founder Societies urged the formation of a committee to enter upon the formulation of those ethical principles which would be appropriate to the entire engineering field. The organization of this committee was undertaken by the President of the American Engineering Council (AEC), which then existed and which had at its head Alonzo J. Hammond, a Past-President of American Society of Civil Engineers. Each of the national societies constituent to AEC was asked to appoint through its board of directors a member of an engineers' joint committee on ethics. This was done, and the committee has steadily gone forward in the effort to formulate a code of ethics which is adequate in the field of engineering and yet is sufficiently specific to be a sound directive to the young engineers as well as an inspiration for the young and the old.

In this formulation, it has been the effort to include only items which are definitely rules of right conduct that are fundamental in social relations and that are frequently enough violated in engineering relations to make it desirable to have the rules in formal adoption, at the same time avoiding features of practice which may be changed as a consequence of current modification of customs and also avoiding features that are dealt with as matters of law through statutory processes or are dealt with as tenets of religion.

The AEC, which had been supported by the Founder Societies, was dissolved and the Engineers' Council for Professional Development (ECPD) undertook the sponsorship for this committee. Therefore three additional societies, which were constituents of ECPD but had not been constituents of AEC, added their representatives to the committee. The group of societies now comprises the following: American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, American Institute of Electrical Engineers, The Engineering Institute of Canada, The Society for the Promotion of Engineering Education, American Institute of Chemical Engineers, National Council of State Boards of Engineering Examiners, and American Institute of Consulting Engineers.

The representative of each society is a man well-known in engineering life, and most of the individuals are past presidents of the society represented or former chairmen of its committee on ethics or committee on professional conduct. In certain instances the representative is both a past president and a former or present chairman of his society's committee on ethics.

The committee finally approved a formulation containing 31 items. This formulation is denominated "Canons of Ethics for Engineers." Here the word "canons" is used instead of the word "code" because many of the engineering societies publish codes of practice that are purely questions of science or of law or of convenience, and it seems desirable to distinguish clearly between the ethical principles and the codes of practice. The precedent of the American Bar Association is a perfectly good one for the use of the word "canons" in this situation.

The 31 items were reported to the ECPD for its consideration, and after discussion Council referred the proposed canons, with the proposal for adoption, to its constituent societies for consideration by their governing boards.

It should be remembered that the ECPD has no authority of itself to impose practices on the engineering field, but it is a representative organization established for the purpose of proposing measures for improving engineering relations and recommending the same to its constituent societies. Then, if the constituent societies approve, the ECPD can proceed with the introduction of the idea as a fixed process in the engineering field.

The action of ECPD was to lay the proposed canons of ethics before its constituent societies with the request for comments or instructions relating to the formulation, and particularly for recommendations of elimination of any items which in the opinion of any board might appropriately be omitted or recommendations of any additional items which in the opinion of any board ought to be included but are omitted in the submitted draft.

Much urgency has been expressed for a very brief code of ethics, partially on the ground that it would be more convenient for printing with various papers, or the ground that it would be easier for young engineers to familiarize themselves with the items; but it may be justly stated that matters of convenience are not fair grounds for judgment of ethical principles. All wish for brevity in such a formulation, but we should not hesitate to have as many items as are appropriately needed for our situation.

If a formulation is finally and formally adopted, it may be assumed that the ECPD will have a pamphlet printed which may be provided to their members by the engineering societies in a manner analogous to the manner of circulation of the pamphlets previously referred to which are issued by the American Bar Association and the American Medical Association. Then each engineer would have in his possession a copy of the pamphlet which he could cherish and utilize in a manner which he felt most desirable.

At the present time the board of directors of the AIEE has approved the ECPD proposed canons of ethics, with suggestions of

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moderate changes of phraseology. The same is true of the council of the Society for the Promotion of Engineering Education (SPEE). The American Institute of Consulting Engineers (AICE), after very careful study by its council, has approved the formulation with the suggestion of very considerable changes in the order of the items and modifications of phraseology. The ASME council has indicated that it desires to co-operate with other societies in securing a uniform code of ethics for the engineering field, and it approves in principle the ECPD proposed canons, leaving it now for its committee on professional conduct to advise with it as to any recommendation which the council should make to ECPD. The board of direction of ASCE has the matter still under consideration as also has the council of the Engineering Institute of Canada.

The Detroit Engineering Society, which is recognized as a well-organized and well-managed local society, has adopted the ECPD canons, and these canons are under consideration by other local societies.

The AIEE has taken an important place in leadership, along with SPEE and AICE, in the approval of these proposed uniform Canons of Ethics for Engineers.

Proposed Canons of Ethics for Engineers

FOREWORD

Justice, courtesy, and sincerity, exercised with honesty, wisdom, and mutual interest between men, make the foundation of ethics.

This ethical code is prepared for the guidance of engineers and engineering students and is aimed to express a consensus of considered judgment on certain matters of common interest to engineers, especially such matters as may not have obvious ethical solutions. Ethics should be more than passive observance of a code of "don'ts" in the life of an engineer. They should be recognized as dynamic principles guiding his conduct and his way of life.

The principles are briefly set forth in what follows.

PROFESSIONAL LIFE AND EMPLOYMENT

1. The engineer will avoid conduct and practices likely to discredit the honor and dignity of the engineering profession.

2. He will attempt to co-operate in building up the engineering profession by interchanging information and experience with other engineers and students and by contributing to the work of engineering societies, schools, and the scientific and engineering press, without disclosing confidential matter.

3. He will present clearly the consequences to be expected from the deviations proposed if his engineering judgment is overruled by nontechnical authority in cases where he is responsible for the technical adequacy of engineering work.

4. He will endeavor to protect the engineering profession and all reputable engineers from misrepresentation and misunderstanding.

5. He will take care that credit for engineering is attributed to those who, insofar as his knowledge goes, are the real authors of the work.

6. He will maintain the principle that unduly low compensation for engineering employment tends toward inferior and unreliable results and is to the disadvantage of his profession.

7. He will not advertise his work or merits in a self-laudatory manner or in a way injurious to the dignity of his profession.

RELATIONS WITH OTHER ENGINEERS

8. The engineer will not, directly or indirectly, injure the reputation or business of another engineer.

9. He will not try to supplant another engineer in a particular employment after becoming aware that decision to employ the other has been reached.

10. He will not compete with another engineer on the basis of charges for work by underbidding after he has been informed of the charges named by the other.

11. He will not use personally the advantages of a salaried position to compete unfairly with another engineer.

12. He will not knowingly review the work of another engineer, for the latter's client or employer, without the other engineer's knowledge unless the latter's connection with the work has terminated.

13. He will not knowingly become associated in responsibility for engineering work with engineers who do not conform to ethical practices.

RELATIONS WITH CLIENTS AND EMPLOYERS

14. The engineer will endeavor, insofar as it is possible, to secure justice between his client or employer and the contractor when dealing with contracts.

15. He will act in professional matters for each client or employer as a faithful agent or trustee.

16. He will not accept compensation, financial or otherwise, from more than one interested party for the same service, or for services pertaining to the same work, without the consent of all interested parties.

17. He will not, without the full knowledge and consent of his client or employer, have an interest in any business which may bias his judgment regarding engineering work for which he is employed or which he may be called upon to perform, or have an interest in a business which may compete with the business of his client or employer.

18. He will not be financially interested in the bids as a contractor on competitive work for which he is employed as an engineer unless he has the consent of his client or employer.

19. He will not accept commissions or allowances, directly or indirectly, from contractors or other parties dealing with his client or employer.

20. He will make his status clearly understood to his client or employer before undertaking an engagement if he may be called upon to decide on the use of inventions, apparatus, or any other thing in which he may have a financial interest.

21. He will regard it his duty to guard against dangerous elements in apparatus, structures, or plant, or dangerous conditions of operation therein, and upon observing such conditions in work with which he is associated, he will call them to the attention of his client or employer. If dangerous conditions persist with his knowledge, he is not fully relieved of his responsibilities.

22. He will, when he is a public officer, recognize his limitations and, under such conditions, retain and co-operate with other engineering experts and specialists whenever such co-operation may be serviceable.

RELATIONS WITH THE PUBLIC

23. The engineer will interest himself in the public welfare and be ready to apply his special knowledge, skill, and training for the benefit of mankind.

24. He will assist public officials and others in attaining a fair and correct general understanding of engineering matters, extend the public knowledge of engineering, and discourage untrue, unfair, and exaggerated statements regarding engineering.

25. He will recognize the fact that meetings of engineering societies and the engineering press provide the proper forum for technical discussions and criticisms, and also that clear statements of facts relating to engineering enterprises are often of value to the public when they are prepared for laymen's understanding and released by competent authority through the public press.

26. He will not issue *ex parte* statements, criticisms, or arguments on matters connected with public policy which are inspired or paid for by private interests unless he indicates on whose behalf he is making the statements.

27. He will not express publicly an opinion on an engineering subject without being informed as to the facts relating thereto.

28. He will express no opinion which is not founded on adequate knowledge and honest conviction while he is serving as a witness before a court, commission, or other tribunal.

29. He will not lend his name to any questionable enterprise or engage in any occupation contrary to law.

30. He will make provisions for safety of life and health of employees and of the public who may be affected by the work for which he is responsible.

31. He will carry on his work in a spirit of fairness and loyalty to associates, subordinates, and employees, fidelity to the public needs, and devotion to high ideals of courtesy and personal honor.

Prepared by a joint committee from national engineering societies (American Institute of Chemical Engineers, American Institute of Consulting Engineers, American Institute of Electrical Engineers, American Institute of Mining and Metallurgical Engineers, American Society of Civil Engineers, American Society of Mechanical Engineers, Engineering Institute of Canada, National Council of State Boards of Engineering Examiners, Society for the Promotion of Engineering Education) with sponsorship of Engineers' Council for Professional Development.

VIII—Influence of Research on Engineering Developments

L. W. CHUBB
FELLOW AIEE

Between World Wars I and II the value of scientific research was recognized in the United States. The years of normal research which have been compressed into a period of months in World War II are a tremendous factor in the winning of the war and will have a profound effect on the postwar world. The many war developments which are the result of research in the electrical and other fields may be expected to revolutionize the electrical industry.

IT IS HAZARDOUS to make predictions; yet it is proper at this time to consider the effect of current and postwar research on engineering developments. In spite of the glaring contrast between the role of scientific research in the period of the last war and its part in the present conflict, the experiences following World War I offer the most helpful standard in present evaluations of postwar activity.

Before the last war American scientific research lagged far behind that of our chief enemy. We were industrially vigorous; we had outstanding inventers and engineers; but our research was relatively weak in every field except agriculture. There were a few good research laboratories in industry and creditable activities in some of the leading universities. On the whole, however, science was not appreciated as the foundation of progress in engineering, and the ease with which the material needs of a nation opulent in natural resources could be satisfied at home or abroad fostered this attitude. A research career was not particularly attractive to the university student, and, consequently, trained scientific workers with advanced degrees were lacking. Since the universities alone train such men, there was no hope of keeping up with foreign research.

The first war has been called an engineer's war. It was a period of great engineering expansion, but the expansion was limited mostly to techniques already established. Thus, we still depended on imports from Chile for practically all of our nitrates. The airplane was still in its infancy and could not be relied upon even for observation, since a sortie over enemy lines was but an invitation for a dog fight. The radio, although useful, was a crude instrument. Existing knowledge was exploited in its design and application, but little advanced work was undertaken. As a matter of fact, practically no American radio supplies gave service at the front before the Armistice was signed. Automotive transport may be taken as a final indication of technological primitiveness: the art was so immature that our armies had to depend upon rail installations for subsistence and supplies.

Recognition of the necessity of scientific research did not come until we had entered the conflict. Soon after 1917 groups such as the Naval Consulting Board, the National Research Council, and the Chemical Warfare Service were formed to consider and develop new instruments for offense and defense. Some of the most urgent problems which received considerable attention, typical of the research activity at that time, were gas warfare, sound ranging, and submarine detection. Work on new and more effective poisonous gases and on defensive measures against such gases was pursued with considerable success. The location of enemy gun batteries by the sound of their blasts was another problem solved at this time. Then, as in this war, the submarine became a great menace to shipping. Methods of detecting these undersea prowlers were investigated by scientists throughout the country, but the work was not co-ordinated properly.

Much good work was done by the groups of scientists and engineers before the end of the last war. But, in general, improper co-ordination, too little, and too late, characterized the fruit of their work. Nevertheless, the seeds of postwar research had been sown, and the stimulation rather than the immediate results of this war research was responsible for the great scientific and technical advances from which new materials, new processes, new products, and major industries emerged.

In the peace between 1918 and Pearl Harbor, an enormous change in attitude toward research took place. There was a more abundant supply of men with scientific training; there was more research in the universities; industrial-research laboratories increased threefold; and many research foundations were founded to provide new knowledge for engineering applications. Today, the public expects and looks for change and progress; advances in any field are items of news; and any industry or company that fails to utilize new discoveries and new techniques is soon hopelessly out of date.

In contrast with the last war, steps were taken even before Pearl Harbor to mobilize the scientific workers of the nation. The blitz tactics, said to be an American idea adapted by Germany, called for radically different tools of combat, defense, communication, and transport. Fortunately, we had two years for observation and preparation before formally declaring war. The need of further developments in science was evident, particularly in engineering, physics, metallurgy, and chemistry. Practically all branches of scientific endeavor have been called upon to furnish the allies with the devices and supplies needed to meet the

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present situation. Existing statutes, creating the American Academy of Sciences and the National Research Council and allowing appropriations for scientific research and development, were fortunately available. Vast sums were granted through the newly organized Office of Scientific Research and Development to carry on scientific development of instruments of war. These organizations brought together large groups of research men. The leading scientists in the country were provided with the necessary laboratory facilities to plan and execute an enormous amount of research work. In addition to the work in the special laboratories, OSRD has contracted for research and development, on a cost basis, in many industrial and college laboratories. Similarly, groups including the Army and Navy have contracted for development work in the laboratories of industry where production could immediately and efficiently follow. Never before in the United States nor, indeed, in any other country, has such intensive scientific activity been so greatly and successfully instigated.

It has often been said that at least ten normal years of research have been accomplished in the last two years. This is probably a conservative estimate, particularly when we consider the prompt application of the ideas and discoveries. Conception, research, development, engineering, production, and utilization often have been compressed into a period of months rather than the traditional seven to ten years from test tube to market.

There can be no doubt that this vast undertaking has been a vital factor toward the winning of the war and that the new knowledge gained will have a profound influence upon postwar developments. Besides the weapons, the defense methods, and the physical equipment emerging from war research, many new and valuable materials, processes, and scientific principles will be available for engineering application.

If our peacetime developments are to be measured by the wartime accomplishments, the future will be a bright one. By comparison the results of 1917–18 are dwarfed; yet the technological advances following that conflict were climaxes in our industrial and social history. The present postwar engineering outlook promises to be more epochal, but there probably will be some delay this time in the application of new research to new products and services. The last war produced no tremendous, immediate market for consumer's goods, because no serious curtailment of such goods was necessary in our relatively short engagement in the war. The present necessary curtailment has created a vast and urgent demand. This demand for goods and services, coupled with the task of maintaining employment at a maximum, requires a prompt reconversion of industry. Old models in production or those which were just coming into production and for which tools are available, certainly should fill these needs and facilitate the transition from war to peace.

The future of the electrical industry, a typical one in many ways, suggests a few of the technological advances which present and subsequent research affords. During the war, the electrical industry has been contributing on two principal fronts. Power equipment and heavy machinery have been limited to the production front and to Naval installations. Electric equipment for communication, auxiliary devices, control, regulation, instrumentation, and low-power machinery have been serving on the firing line, in the air, on the ships—in any installation of consequence throughout the world. The research and development necessary for obtaining the most effective weapons has been stupendous and has disclosed new scientific information, new circuits, new devices, and new principles of operation which will serve as the basis of engineering applications for years to come.

Restrictions limit the information which can be given concerning many of the products resulting from research work. However, a mere mention of some of the fields of activity suggests some of the things useful in war and applicable in peace—electronics, radio, radar, gunfire control, stabilization of guns and moving equipment, servomechanisms, navigation aids, and control devices. A great many of the war developments will find almost instant application with little or no further modifications. Radar is a good example. With it our airplanes and ships may travel at scheduled speeds, assured of safety in fog or darkness. Other techniques utilizing ultrashort radio waves can be adapted to communications, and the increased number of frequency bands, beam transmission, and limitations of range will help eliminate interference. The general adoption of short-wave communication for load dispatching, supervisory control, and remote metering in our great utilities is reasonably certain. The very successful servomechanisms, control equipment, and electronic devices can be applied in peacetime with little additional development or engineering attention.

In the electrical industry, there will be no major problem of conversion as far as capital goods are concerned. Installed capacity has been greatly increased for government and war purposes. In spite of this, there will be new requirements in the power field to meet the demand of industries released from governmental restrictions and engaged in their peacetime production—production which will be stimulated by the war research and development in all fields.

Research in other than electrical fields has produced information and materials which also will be valuable in the electrical industry. New and more stable lubricants will find general application. New high-strength high-temperature alloys developed for superchargers and gas turbines will permit the use of higher temperatures in steam turbines. New compositions of matter having unusual properties will be useful as high-temperature insulation and cooling media; and many metallurgical products and methods of fabrication, in the long run, will revolutionize our industry with entirely new appliances and better more efficient machinery.

Although the predictions of the new life in the world to come immediately after the war have been exaggerated greatly, the outlook for the future is exceedingly bright; and it seems fortunate that the empty shelves and the accumulated buying power will permit great industrial activity immediately after the surrender and allow time for the engineers to remold the world with the new scientific knowledge of which there is an abundance.

Apparatus Imitates Sea Motion

Bolted to the steel table at the left, sea-borne equipment is rocked back and forth by this Western Electric Company testing apparatus as it would be during an ocean voyage

INSTITUTE ACTIVITIES

Winter Technical Meeting to Feature Wartime Developments

Arrangements are being made for the winter technical meeting, which will be held in New York, N. Y., January 22–26, 1945, with headquarters in the Engineering Societies' Building. Many wartime developments with interesting postwar applications will be presented in some 32 technical sessions and conferences. Also during this meeting the Edison Medal will be presented. In addition the Institute of Radio Engineers will hold their winter technical meeting concurrently, January 24–27, to permit engineers interested in radio and communication work to attend both meetings in one trip. The programs of both meetings will be co-ordinated, and as in the past a joint AIEE–IRE evening session is planned.

TECHNICAL SESSIONS AND CONFERENCES

Among the sessions and conferences which present wartime developments with postwar applications are two air-transportation sessions; sessions on industrial control, industrial power applications, and arc welding; a conference on wartime practices on distribution systems and their effect on operation and system design; and a conference on statistical methods applied to quality control. The development of the propeller milling machine, which has helped improve and accelerate the ship program, will be presented in two papers. Formerly the cutting of the spiral helix of a propeller blade was an arduous hand operation. The development of this machine tool has been made possible only by the close co-operation of electrical engineers and mechanical engineers. In another paper basic Selsyn systems and the characteristics of their components with servo mechanisms will be described. This type of control has had many military and industrial applications with new developments in the older principles and new applications of modified designs. Power-station auxiliaries, carrier-current applications, relays, circuit breakers, electrolysis, lightning, and insulation will be the subjects of other sessions of particular interest in the central-station field. Details will be given in the January issue as the program develops.

SMOKER

To afford recreation and an opportunity to get together with friends in pleasant surroundings a smoker will be held Tuesday evening, January 23, at the Hotel Commodore. Insofar as possible all of the features of this affair will be provided as in previous years. Tickets, including the dinner and show, will be six dollars per person, including tax. Tables for ten can be reserved by advance payment. Checks should be made out to "Special Account, National Secretary, AIEE."

THEATER TICKETS

Every effort is being made to have choice tickets available for the best shows. These are being reserved for the evenings of Wednesday, January 24, and Thursday, January 25. Preference will be given to requests from out-of-town members. Members desiring tickets for specific performances on these or other dates may write to Institute headquarters enclosing checks made out to "Special Account, National Secretary, AIEE." The theater-ticket committee will do its utmost to take care of such requests.

A limited number of seats are now available for "Oklahoma," "Song of Norway," and "Voice of the Turtle." Ticket prices follow:

Song of Norway	$6.00
Voice of the Turtle	4.20
Oklahoma	4.80

COMMITTEES

The personnel of the 1945 winter technical meeting committee, which is making the arrangements, is as follows: J. F. Fairman, chairman; F. A. Cowan, W. S. Hill, M. D. Hooven, A. E. Knowlton, C. S. Purnell, C. C. Whipple, R. J. Wiseman.

AIEE Industrial Distribution Report Available Soon

The Institute's committee on industrial power applications, working under the chairmanship of J. Grotzinger, of the Goodyear Tire and Rubber Company, has been at work for some time preparing a report on "Electric-Power Distribution for Industrial Plants." This new publication will be available shortly.

The report co-ordinates the contributions of some 40 specialists from the following industries: Aircraft, automobile, cable, chemical, copper, electric equipment, factory insurance, mining, oil, photographic equipment, rubber, steel, and the utilities. It is intended to promote the use of sound engineering principles in the design of electric-power-distribution systems for industrial plants and in the selection of equipment for those systems. For the purposes of the report the distribution system is considered as extending from the point of entrance of the power-company service or the plant generating bus to the terminals of the utilization devices. This includes high-voltage substations, distribution substations, feeders, circuits, switch centers, and protective equipment. The committee wishes it fully understood that the report is not an AIEE Standard, and the recommendations are not intended in any way to be mandatory or restrictive.

The function of an industrial-plant distribution system is to receive power at one or more bulk power sources and deliver it to the individual utilization devices or loads, such as motors, lights, welders, and furnaces. The effectiveness with which a distribution system fulfills this function is measured in terms of voltage regulation, service continuity, flexibility, efficiency, simplicity, maintenance, and cost. The proper distribution system to use in an industrial plant is the one which will provide adequate, economical, and safe electric service to the plant loads now, and also with an eye to the future. The selection of the system to be used involves consideration of not only adequate service to existing loads and first cost, but also the cost of operation, maintenance, and modification of the system to meet future changing loads. At no time should a saving in cost be made by a sacrifice in reasonable safety to life or property. The report within its scope analyzes the service requirements, voltage-regulation problems, load characteristics, and distribution-system characteristics, and it also deals with the selection of equipment for distribution systems. Operating and maintenance problems are dealt with only insofar as they affect system and equipment selection.

To give a comprehensive picture of the vast amount of valuable data made available to industrial engineers through the publication of this report would require more space than is here available. A listing of the six chapter headings, however, will give a brief view of the scope of the work. They are as follows: System planning; primary substations and feeders; transformers, primary switchgear, and low-voltage feeder protection; low-voltage feeders, panel boards, bus distribution systems, and load circuits; fault-current calculations; wires and cables.

The Institute's committee on industrial power applications believes that this publication fills a long-felt need in the industrial-engineering field and may be the forerunner of similar reports covering other phases of industrial engineering. The new report, now on the press, is a pamphlet of 112 pages with very heavy paper cover. It is profusely illustrated. Copies will be available from AIEE headquarters at one dollar each with discounts permitted on quantity orders.

1944 December Supplement Contents Announced

Technical papers presented before AIEE technical meetings during 1944 and not published in the monthly *Transactions* section of *Electrical Engineering* or in the June supplement will appear in the December 1944 "Supplement to Electrical Engineering—Transactions Section." The December supplement will contain 45 technical papers, discussions of those papers, and discussions of the papers already published in the July–December monthly sections. Contrary to the announcement made in the September issue of *Electrical Engineering* there will be only one year-end supplement because, although there is a large amount of material to be published, it is not enough to necessitate two supplements as had been anticipated. Issuance of the December supplement will complete publication of papers and discussions presented before the 1944 North Eastern District meeting in Boston, Mass., April 19–20; the 1944 summer technical meeting in St. Louis, Mo., June 26–30; and the Los Angeles technical meeting in Los Angeles, Calif., August 29–September 1.

Copies of the supplement will not be available until some time after the first of the

year, at which time published copies will be mailed to those who entered advance orders. Others then may obtain copies at 50 cents each from the AIEE order department, 33 West 39th Street, New York 18, N. Y.

Papers appearing in the December 1944 supplement, abstracts of which have been published in *Electrical Engineering* in advance of the meetings are:

Air Transportation

44-81—A-C and D-C Short-Circuit Tests on Aircraft Cable; *J. C. Cunningham* (*A '42*), *W. M. Davidson* (*A '42*). Abstracted in April 1944 issue, page 145.

44-82—Damping Cylinders for Aircraft Gyroscopes; *F. R. Sias, Jr.*, *J. H. Wright* (*M '43*). Abstracted in April 1944 issue, page 146.

44-150—Design Considerations in Aircraft Instruments to Meet War Service; *C. F. Savage* (*M '43*), *J. M. Whittenton* (*A '37*). Abstracted in the June 1944 issue, page 226.

44-180—Alternating Versus Direct Current for Aircraft-Radio Power Supply; *D. E. Fritz* (*A '43*), *C. K. Hooper*. Abstracted in the August 1944 issue, page 309.

44-183—Electrically Heated Clothing; *G. H. Wetring*. Abstracted in the August 1944 issue, page 309.

44-189—Design of an Ignition System for an 18-Cylinder Aircraft Engine; *J. R. Harbuss*. Abstracted in the August 1944 issue, page 310.

44-194—Aircraft-Electric-Accessory-Vibration Investigation; *D. R. Miller* (*A '42*). Abstracted in the August 1944 issue, page 310.

44-203—A 120-Volt D-C Aircraft Electric System; *L. M. Cobb* (*A '34*). Abstracted in the August 1944 issue, page 311.

44-205—Problems in Applying Protectors to Electric Aircraft Motors; *L. W. Buell* (*M '44*). Abstracted in the August 1944 issue, page 311.

44-225—Cable Used for Transmitting Electric Energy in Airplanes; *M. F. Peters, Jr.*, *J. J. Phillips*, *Max Kronstein*, *H. B. Joslow*. Abstracted in the August 1944 issue, page 313.

44-225—A-C Supplies for Services in Large Aircraft—a British View; *E. J. Eavenson, Jr.*, *B. Shearer*.

44-227—Aircraft-Engine-Accessory Vibration; *John Tyler*.

44-229—Plastics in Aircraft Electricity; *E. B. Cooper*. Abstracted in the August 1944 issue, page 313.

44-231—New Test Chambers for Aircraft Electric Apparatus; *E. R. Summers* (*A '38*), *J. F. Stetle* (*A '42*). Abstracted in the August 1944 issue, page 313.

44-235—Airplane Engine and Propeller Test-Cell Lighting; *D. H. Tuck*. Abstracted in the August 1944 issue, page 313.

44-237—Impedance of 400-Cycle Three-Phase Power Circuits on Large Aircraft and Its Application to Fault-Current Calculations; *C. K. Chapman* (*A '41*), *L. M. Olmsted* (*M '30*). Abstracted in the August 1944 issue, page 313.

44-241—Design Considerations for D-C Aircraft Generators; *J. D. Miner, Jr.* (*M '42*). Abstracted in the August 1944 issue, page 314.

Communication

44-126—Developments in the Field of Cable and Radiotelegraph Communications; *Haraden Pratt* (*F '37*), *J. K. Roosevelt* (*M '30*). Abstracted in the June 1944 issue, page 227.

44-127—American Telegraphy After 100 Years; *F. E. d'Humy* (*F '30*), *P. J. Hans* (*A '09*). Abstracted in the June 1944 issue, page 227.

44-128—Telegraphy in the Bell System; *J. A. Duncan*, *R. D. Parker* (*M '14*), *R. E. Fiero* (*M '30*). Abstracted in the June 1944 issue, page 227.

Domestic and Commercial Applications

44-154—Load-Calculation Procedure for Electric-Panel Space Heating; *B. F. Raber, F. W. Hutchinson*. Abstracted in the June 1944 issue, page 228.

Electric Machinery

44-169—Progress in Impulse Testing of Transformers; *J. H. Hagenguth* (*M '44*). Abstracted in the June issue, page 229.

44-176—Differential Leakage With Respect to the Fundamental Wave and to the Harmonics—Integral-Slot and Squirrel-Cage Windings; *M. M. Liwschitz* (*M '39*). Abstracted in the June 1944 issue, page 229.

Electric Welding

44-105—The Design of Low-Voltage-Welding Power Distribution; *C. A. Adams* (*F '13*), *J. R. Fletcher* (*A '36*), *A. C. Johnson* (*A '42*). Abstracted in the June 1944 issue, page 229.

44-125—An Improved Electronic Control for Capacitor-Discharge Resistance Welding; *H. J. Bichsel* (*A '43*), *E. T. Hughes*. Abstracted in the June 1944 issue, page 230.

Electrochemistry and Electrometallurgy

44-100—Treatment and Casting of Metals by Electromagnetic Forces; *W. W. Hoke*. Abstracted in the June 1944 issue, page 230.

44-165—Characteristics of Chlorinated Impregnants in D-C Paper Capacitors; *L. J. Berberich* (*M '36*), *C. V. Fields* (*A '41*), *R. E. Marbury* (*M '36*). Abstracted in the June 1944 issue, page 230.

Electronics

44-11—Analysis of Rectifier Circuits; *E. F. Christensen* (*A '39*), *C. H. Willis* (*F '42*), *C. C. Herskind* (*M '40*). Abstracted in the June 1944 issue, page 230.

44-78—Development of Excitron-Type Rectifier; *H. Winograd* (*M '39*). Abstracted in April 1944 issue, page 146.

44-145—Design of an Electronic Frequency Changer; *C. H. Willis* (*F '42*), *R. W. Kierulf* (*A '42*), *E. F. Christensen* (*A '39*), *B. D. Bedford* (*M '43*). Abstracted in the June 1944 issue, page 231.

Industrial Power Applications

44-144—The Electronic Converter for Exchange of Power; *F. W. Cramer* (*M '40*), *L. W. Morton* (*A '38*), *A. G. Darling* (*M '44*). Abstracted in the June 1944 issue, page 231.

44-236—Vacuum-Tube Radio-Frequency Generator—Characteristics and Applications to Induction Heating; *T. P. Kinn* (*M '44*). Abstracted in the August 1944 issue, page 314.

Instruments and Measurements

44-161—A Resonant-Cavity Method for Measuring Dielectric Properties at Ultrahigh Frequencies; *C. N. Works* (*A '40*), *T. W. Dakin*, *F. W. Boggs*. Abstracted in the June 1944 issue, page 232.

Marine Transportation

44-139—Fault Protection on Shipboard A-C Power-Distribution Systems; *H. G. Rickover* (*M '44*), *P. N. Ross*. Abstracted in the June 1944 issue, page 232.

Power Transportation

44-106—The Effect of Weather on the System Load; *H. A. Dryar* (*M '43*). Abstracted in the June 1944 issue, page 232.

44-107—Conditions Controlling the Economic Selection of Prime Movers; *B. G. A. Skrotzki*. Abstracted in the June 1944 issue, page 232.

Power Transmission and Distribution

44-114—The Measurement of Lightning Currents in Direct Strokes; *G. D. McCann* (*M '44*). Abstracted in the June 1944 issue, page 233.

44-115—Transmission-Line Electric Loadings; *S. B. Crary* (*M '37*). Abstracted in the June 1944 issue, page 233.

44-117—Capacitor Installation at Newport News; *V. R. Parrack* (*M '37*), *E. L. Harder* (*M '41*). Abstracted in the June 1944 issue, page 233.

44-118—Capacitors, Condensers, and System Stability; *J. W. Butler* (*M '38*), *T. W. Schroeder* (*M '44*), *W. Ridgway* (*A '41*). Abstracted in the June 1944 issue, page 233.

44-130—Impulse Strength of Insulated-Power-Cable Circuits; *Herman Halperin* (*M '26*), *G. B. Shanklin* (*M '29*). Abstracted in the June issue, page 233.

44-131—Cyclic Movement of Cable—Its Causes and Effects on Cable-Sheath Life; *C. S. Schifreen* (*M '43*). Abstracted in the June 1944 issue, page 233.

44-215—An Analysis to Determine the Optimum Bussing Arrangements and Transmission Capabilities at Grand Coulee; *B. V. Hoard* (*M '36*), *G. W. Bills* (*A '38*). Abstracted in the August 1944 issue, page 314.

44-226—New 138-Kv Underground Cable Lines in Los Angeles; *C. G. Mansfield* (*M '42*). Abstracted in the August 1944 issue, page 314.

AIEE Board of Directors Meets

At the regular meeting of the AIEE board of directors held at Institute headquarters, New York, N. Y., November 2, 1944, the board confirmed approval by the executive committee, for submission to the American Standards Association for adoption as an American Standard, a proposed revision of American Standard Z32.5, "Graphical Symbols for Telephone, Telegraph, and Radio Use."

Also confirmed were the following actions of the executive committee as of September 27, 1944: 12 applicants transferred to the grade of Fellow; 89 applicants transferred, and 57 elected to the grade of Member; 219 applicants elected to the grade of Associate; 421 Students enrolled.

Reports were presented of meetings of the board of examiners held September 21 and 29 and October 19, 1944, and the recommendations adopted at those meetings were approved by the board of directors. Upon recommendation of the board of examiners, the following actions were taken: 22 applicants were elected to the grade of Member; 74 applicants were elected, and one was reinstated to the grade of Associate; 200 Students were enrolled.

Upon petition, the members of the board present voted unanimously for the election of Dugald C. Jackson as an Honorary Member of the Institute, the votes of absent members to be obtained by letter ballot, as the constitution specifies that Honorary Members shall be elected by the unanimous vote of the entire board. (Affirmative votes subsequently were received from all absent board members.)

The finance committee reported budget expenditures amounting to $29,144.76 in August, $28,895.93 in September, and $38,683.02 in October and submitted a budget for the appropriation year beginnning October 1, 1944, amounting to $450,000, which was approved.

A new formula, increasing the allotment of funds to Sections, as recommended by the Sections committee and the finance committee and applied to the 1944–45 budget, was adopted as a permanent policy, the Institute bylaws to be amended accordingly.

Approval was given to the dates, April 25–26, for the previously authorized North Eastern District technical meeting in Buffalo, N. Y., in 1945.

Plans of the 1945 winter technical meeting committee were reported and approved, including a joint evening session with the Institute of Radio Engineers, a smoker, and possibly technical inspection trips if they can be arranged.

Authorization was given for a Pacific Coast technical meeting in Seattle, Wash., in August 1945, the exact dates to be decided later.

Upon recommendation of the Standards committee, W. P. Dobson was appointed AIEE representative on the Joint Committee for Development of Statistical Applications in Engineering and Manufacturing.

In response to a request of the Mexico Section, the board, upon recommendation of the committee on planning and co-ordination, voted to grant to the Mexico Section financial assistance for an occasional meeting of the nature of a District meeting.

P. L. Alger, R. T. Henry, T. G. LeClair, S. H. Mortensen, and C. W. Ricker were elected board members to serve on the national nominating committee, in accordance with the bylaws. J. F. Fairman and N. E. Funk were designated as alternates.

The board confirmed the reappointment by the president of H. S. Osborne as an AIEE representative on the Standards council of the American Standards Association for the three-year term beginning January 1, 1945. H. E. Farrer, H. L. Huber,

and E. B. Paxton were reappointed alternates on the Standards council for the calendar year 1945.

The reappointment by the president of J. C. Parker as AIEE representative on the National Technical Civil Protection Committee for the administrative year 1944–45 was confirmed.

G. T. Harness having declined reappointment as the Institute's representative this year on the Radio Technical Planning Board, H. A. Affel, chairman of the committee on communication, was appointed in his place.

W. C. White, chairman of the committee on electronics, was appointed chairman of the special committee advisory to the AIEE representative on the Radio Technical Planning Board, in place of G. T. Harness, who declined reappointment this year.

Minutes of the meeting of the board of directors held August 2, 1944, were approved.

The board approved a letter sent jointly to Secretary of State Hull by the presidents of the four Founder Societies and the American Institute of Chemical Engineers, transmitting a suggested program for industrial control of postwar Germany, resulting from a study of the technical and industrial problems involved in the permanent disarmament. This plan pointed out the fact that an indiscriminate destruction of the German industrial system, failing to differentiate between the wartime and peacetime economy of the country, would penalize not only the owners of the materials destroyed, but the world as a whole, and outlined certain steps which, if followed, would make it impossible for Germany to wage or prepare for war, and would do this with the least disturbance to the normal economy of Western Europe.

Other subjects were discussed, reference to which may appear in this or future issues of *Electrical Engineering*.

Those present at the meeting were:

President—C. A. Powel, East Pittsburgh, Pa.

Past President—N. E. Funk, Philadelphia, Pa.

Vice-Presidents—L. A. Bingham, Boulder, Colo.; C. B. Carpenter, Portland, Oreg.; M. S. Coover, Ames, Iowa; J. F. Fairman, New York, N. Y.; W. J. Gibson, Toronto, Ontario, Canada; R. T. Henry, Buffalo, N. Y.

Directors—P. L. Alger, Schenectady, N. Y.; K. L. Hansen, Milwaukee, Wis.; C. M. Laffoon, East Pittsburgh, Pa.; T. G. LeClair, Chicago, Ill.; M. J. McHenry, Toronto, Ontario, Canada; C. W. Mier, Dallas, Tex.; S. H. Mortensen, Milwaukee, Wis.; W. B. Morton, Philadelphia, Pa.; D. A. Quarles, New York, N. Y.; W. R. Smith, Newark, N. J.

National Treasurer—W. I. Slichter, New York, N. Y.

National Secretary—H. H. Henline, New York, N. Y.

Industrial Control Apparatus. The "American Standard for Industrial Control Apparatus, *C*19.1" (AIEE number 15) issued in March 1944 should be corrected in accordance with the following errata tabulation:

Paragraph 15-101—Should read "Contactor ratings . . ."

Paragraph 15-109—Drop words "and numbers"

Bottom page 15—Equation should be $I_1 \times I^2t + 0.25I_m$

Table on page 16—"Medium Duty" should read "65–80"

Paragraph 15-126—Rise for busses, straps, ... etc. should be "50C"

Paragraph 15-132—Equation should be

$$T = \frac{R}{r}(234.5 + t) - 234.5$$

Paragraph 15-146*a*—Should read "Watertight enclosures shall . . . . etc."

Future AIEE Meetings

Winter Technical Meeting
New York, N. Y., January 22–26, 1945

North Eastern District Meeting
Buffalo, N. Y., April 25–26, 1945

Summer Technical Meeting
Detroit, Mich., June 25–29, 1945

SECTION • • • • •

60th Anniversary of First Meeting Celebrated in Philadelphia

The atmosphere of the first recorded meeting of the AIEE held in Philadelphia, Pa., in October 1884 was recalled to an audience of members and guests of the Philadelphia Section and distinguished members of the Institute at a commemorative meeting held on the 60th anniversary of that first historic meeting.

The setting and historical significance of the first meeting was interpreted by National Secretary H. H. Henline (F '43) who followed the outline of the speech delivered on that occasion by Edwin J. Houston, associate of Elihu Thomson and Thomas Edison, who in 1884 was instructor in the Central High School in Philadelphia. Mr. Henline added a note of authenticity to his address by frequent quotations from the minutes of the first meeting and from Professor Houston's original talk on the phenomenon known as the "Edison effect."

Charles A. Powel (F '41), AIEE president, devoted his speech on "Romance in Engineering" to inspiring in his hearers the pioneer's attitude toward improvements on what may seem to be finished products and to exploding the assumption of the casual observer that all the nooks and crannies of electrical science have been explored. As an illustration Mr. Powel pointed out that the modern locomotive is as much an advance over the first locomotive as the first locomotive was over any previous mode of locomotion. New vistas are opening continually—some of them to be found through obvious and routine tasks, others through achievements requiring keen analytical insight and aggressive work, said Mr. Powel.

In his discussion of "Electronics—From Glow to Glamour," W. C. White (M '30), director of the electronics laboratory of the General Electric Company returned to the "Edison effect" of 60 years ago and traced its development down to present-day electronics. Two applications of particular interest described by Mr. White were the magnetic-wire recorder and a modern design of a little publicized lighthouse tube. The ease and simplicity of operation of the recorder was demonstrated by an on-the-spot recording of Mr. White's talk.

Two past presidents of the AIEE, Nevin E. Funk (F '34) and David C. Prince (F '26) also were among the record audience of 230. A dinner which preceded the meeting was attended by 130 persons.

ABSTRACTS • • •

TECHNICAL PAPERS previewed in this section will be presented at the AIEE winter technical meeting, New York, N. Y., January 22–26, 1945, and will be distributed in advance pamphlet form as soon as they become available. Copies may be obtained by mail from the AIEE order department, 33 West 39th Street, New York 18, N. Y., at prices indicated with the abstracts; or at five cents less per copy if purchased at AIEE headquarters or at the meeting registration desk.

Mail orders will be filled AS PAMPHLETS BECOME AVAILABLE

Air Transportation

45-3—Speed-Control System for an Aircraft-Cabin-Supercharger Drive; *F. W. Godsey (M '36), J. D. Miner, Jr. (M '42), O. C. Walley (A '44). 15 cents.* Cabin supercharging is becoming extremely important as ceilings for military aircraft are extended upward. Many different schemes have been worked out for using main-engine power to drive variable-speed blowers at speeds which will maintain the desired airflow and cabin pressure at various altitudes. Two fundamental problems are:

1. Providing a variable-ratio transmission between the engine and the blower.
2. Controlling the blower speed to maintain the required air delivery.

In some cases a third problem arises because the point of air delivery is at a considerable distance from the engine, necessitating either a long transmission of power or the use of long air ducts. Requirements for remote supercharger drives of moderate power may be met by means of a variable voltage electric coupling. By using suitable motor characteristics, the air delivery of a blower connected to such an electric coupling can be controlled by a simple regulator designed to vary current in proportion to voltage. Requirements for the electric equipment are developed and laboratory tests on a nine-horsepower model are presented to demonstrate that the equipment meets the specified performance.

45-5—Simulated High-Altitude Testing of Aircraft Ignition Cables and Connectors; *H. H. Race (F '39), A. M. Ross, Jr. 15 cents.* A simulated-high-altitude test apparatus has been constructed for subjecting shielded ignition-cable-connector spark-plug assemblies to high voltage, high temperature, and reduced pressure, the two latter variables being cycled to reproduce an essential and severe aspect of aircraft-engine operation. Several hundred assemblies of many types have been tested in this way, and the results on test life indicate conclusively the inferiority of conventional lacquered-braid ignition cables and the necessity for positive and permanent sealing of the spark-plug connector. Two components developed during the period have been tested exhaustively and proved to increase test-life substantially:

1. Neoprene-sheathed ignition cables.
2. A composite neoprene-Mycalex integrally molded cable terminal.

Although it does not supplant regular acceptance or manufacturing control testing of ignition cables, the simulated-high-altitude tester fills a definite need for obtaining information on new cables and connectors in advance of engine tests.

45-6—Aircraft Illumination; *W. W. Davies. 15 cents.* This paper discusses generally the desirability of a complete redesign of all lighting of pilot compartments; of sealed beam-type landing lights; of such changes in landing lights as automatic bulb changers similar to those used in airway beacons; of more complete lighting of individual airport runways; of eliminating the flashing lights on the belly and top of the plane; and of the flashing tip and tail lights so as to give adequate visibility from all angles to approaching aircraft. With pilot-compartment lighting, it is pointed out that there is a general need for over-all illumination of the cockpit primarily for use in checking controls and instruments prior to take off and after landing as well as for use in completing paper work in the cockpit. Instrument lighting for en route flying, however, is extremely important, and it is essential to have all instruments lighted to the same degree with a provision for changing the intensity by means of a suitable control. Use of special lighting as well as improved over-all cockpit lighting, such as fluorescent lights, spot sources of ultraviolet for lighting charts and records, so-called "red light" for the illumination of instruments, and other such developments. The sealed-beam-type landing light has been suggested to the Civil Aeronautics Authority for further study. It also is pointed out that increased operations, both in terms of volume and number of aircraft, along with the possibility of improved landing equipment permitting operation in more inclement weather would make the "ribbon lighting" of runways desirable. Elimination of belly and top flashing lights on aircraft is recommended in view of reflections in the cockpit of the airplane from these lights in mist or overcast conditions. Improved methods for the installation of reading lights in the airplane cabin, for lights on loading and unloading equipment for both passengers and cargo, and for aircraft servicing lights also are considered and advantages and disadvantages discussed.

Automatic Stations

45-7—Supervisory Control for New Chicago Subway; *W. A. Derr (A'43), C. J. Buck, J. A. Stoos. 15 cents.* Visicode supervisory control is used to control the power supply to the 4.9 miles of subway in Chicago, which were put into operation in October 1943. In addition to controlling and supervising circuit breakers, the supervisory equipment also controls and supervises the position of ventilating fans throughout the subway and supervises the position of other devices. The supervisory-control dispatching-office equipment is located on the 12th floor of the Edison Building. The remote-station supervisory-control equipment is located at eight control centers in the subway.

Because of the scattered location of equipment throughout the subway, special single- and two-wire extensions were constructed from the control centers to provide control and supervision of these devices. The scheme used provides continuous supervision of the continuity of the direct-wire extension circuits. On the automatic-reclosing feeder breakers a new arrangement of supervision was provided. In addition to the standard red and green lamp indications, an amber lamp also is used. The red lamp indicates that the breaker is closed; the green lamp indicates that the breaker is tripped and locked out; and the amber lamp indicates that the breaker is tripped but not locked out. The extra lamp was provided to prevent the possibility of having a breaker automatically reclose while men were working on a faulted section. On all supervisory-control systems built in the past, the change in position of a device always has been indicated by the lighting of a disagreement lamp. The subway installation marked the advent of a new type of indication to indicate an automatic operation—the flashing of the red, green, or amber position-indicating lamp. The flashing-lamp signal has proved to be a definite improvement in locating a unit which has changed position. The compact arrangement of the dispatching-office control equipment places the entire control at the finger tips of a single operator.

Basic Sciences

45-1—Two-Phase Co-ordinates of a Four-Phase Network; *E. W. Kimbark (M'35). 15 cents.* A four-phase five-wire network is analyzed by regarding it as two single-phase three-wire networks with common neutral and then by replacing each of these two networks by their symmetrical-component networks of zero and first order. The resulting substitute quantities are called the two-phase co-ordinates of the four-phase network. Their properties are similar to those of two-phase co-ordinates of a three-phase network. The two first-order networks have voltages and currents which are normally equal in magnitude and 90 degrees apart in phase and which thus constitute a two-phase system. The four substitute networks are independent, if the original four-phase network is symmetrical with respect to two perpendicular axes. Connections between substitute networks for representing 16 types of short circuit on a four-phase network are given both for symmetrical components and for two-phase co-ordinates.

Power Generation

45-4—Evaluation of Electric Distribution Losses in Terms of Generating-Station Capacity; *M. Mortara. 15 cents.* Generally accepted methods are available for estimating the economic value of the energy absorbed by electric losses in a distribution system. There is no consensus however, on the economic evaluation of these losses in terms of their influence upon generating-station capacity requirements. Such evaluation for an electric system of given characteristics can be made by mathematical analysis on the basis of the long-range trend curve, representing the expected development of the system. With appropriate assumptions on the type of curve to be used, a rational method is developed for estimating the deferments in the requirements for new generating capacity obtainable by reduction of power losses. The economic value of such deferments then is calculated, showing that the cost of power losses is comparable with, and may be considerably greater than, that of the consequent energy losses. That factor, therefore, never should be neglected in planning studies.

45-9—Use of Dielectric-Absorption Tests in Drying Out Large Generators; *H. C. Marcroft (A'31). 15 cents.* Dielectric absorption is the name commonly given to the effect which takes place in electrical insulation, when it is subjected to a direct potential, with reference particularly to the manner in which the resulting charging current into the insulation decreases with time. The time rate of change and the magnitude of the observed current are indications of the amount of absorbed moisture (among other things) existing in the insulation of large generators, which apparatus affords a practical application of the dielectric-absorption phenomenon. A newly wound generator or a generator long idle contains moisture in the insulation, which should be removed before full operating voltage is applied to the winding insulation. The method of using the dielectric-absorption effect to determine the state of dryness of large generators is presented as a new means of measurement and one better adapted to giving more information than methods previously used.

Marine Transportation

45-2—Damping Effect of D-C Marine Propulsion Motors on Vibrations Produced in Drive Shafts by Large Propellers; *Bernard Litman (A'42). 15 cents.* D-c machines often are employed in ship-propulsion drives where maneuverability and a wide speed range are required. The d-c machine also has the advantage of serving as a source of damping, if propeller pulsation should coincide with the natural frequency at some speed. This damping force arises because of the fact that any change in speed of the motor will cause a corresponding change in load current and torque. This torque change acts to oppose the original speed change, thus providing an effective damping force. The necessary equations and circuits are developed for calculating this damping effect, and an illustrative calculation is included with actual test values for comparison.

Protective Devices

45-8—Graphical Method of Calculating Fault Currents on Rural Distribution Systems; *F. W. Linder (A'41). 15 cents.* The purpose of this paper is to describe a simple graphical method of calculating fault currents on distribution systems which gives accurate results and saves time and effort in making the calculations. Special reference is given to rural distribution systems of the multigrounded-neutral type; however, the principles of the graphic method may be applied to any system. Fault currents are calculated on current diagrams which are easy to construct on standard rectangular co-ordinate graph paper. The current diagrams are designed for a specific system voltage, and a separate diagram is used for each type of fault. When the fault currents on a system have been calculated by the graphical method, the current diagrams will aid in system operation, because they give a visual picture of the possible fault currents at any location on the system.

PERSONAL • • • •

Dugald C. Jackson (A '87, M '90, F '12) professor emeritus of electrical engineering, Massachusetts Institute of Technology, Cambridge, was elected an Honorary Member of the Institute on November 2, 1944. He was born in Kennett Square, Pa., on February 13, 1865, and received a degree in civil engineering from Pennsylvania State College in 1885. He also has been awarded an honorary doctor-of-science degree by Columbia University and an honorary doctor-of-engineering degree by Northeastern University. Doctor Jackson began his career in

Dugald C. Jackson

1887 as vice-president of the Western Engineering Company, Lincoln, Neb. In 1889 he joined the Sprague Electric Railway and Motor Company, New York, N. Y., as assistant chief engineer, and in 1890 he became a chief engineer for the Edison Electric Company. In 1891, with his brother, W. B. Jackson, Doctor Jackson organized a firm of consulting engineers and also was appointed professor of electrical engineering at the University of Wisconsin, Madison. He maintained this position until 1907 when he joined the staff of the Massachusetts Institute of Technology as professor and head of the department of engineering. Meanwhile, in 1919, he helped to organize the firm of Jackson and Moreland and remained as senior partner until 1930. He retired from the Massachusetts Institute of Technology as professor emeritus in 1935. Doctor Jackson has been a member and chairman of many Institute committees, including the Standards committee, the transportation committee, and the Edison Medal committee, and has served as vice-president (1897–99) and president (1910–11) of AIEE. During the first World War he served as a lieutenant colonel with the United States Army in France. He was a Lamme Medalist in 1931 and received the Edison Medal in 1938; is a member of the American Society of Mechanical Engineers, the American Society of Civil Engineers, the Institution of Electrical Engineering (London, England), the Société Française des Electriciens (Paris, France), the American Institute of Consulting Engineers, and the Engineers' Council for Professional Development; and has written several books and many articles on the subject of electrical engineering.

W. L. Everitt (A '25, F '36) director of operational research, Office of the Chief Signal Officer, United States War Department, Washington, D. C., has been appointed professor and head of the department of electrical engineering, the University of Illinois, Urbana. His duties will begin immediately upon his release from war service. Doctor Everitt was graduated from Cornell University, Ithaca, N. Y., in 1922. In 1926 he received the degree of master of science from the University of Michigan, Ann Arbor, and in 1933 he was awarded the degree of doctor of philosophy by Ohio State University, Columbus. From 1920 until 1922 he taught electrical engineering at Cornell University and after his graduation was employed by the North Electric Manufacturing Company, Galion, Ohio, as engineer in charge of the design and development of private telephone exchanges. Doctor Everitt joined the staff of the University of Michigan as an instructor in electrical engineering in 1924 and remained at that institution until 1926 when he was appointed assistant professor of electrical engineering at Ohio State University. He became associate professor in 1929 and professor in charge of communication courses in 1934 but was sent to Washington in 1942 to direct research for the Signal Corps. Doctor Everitt was recently elected president of the Institute of Radio Engineers.

G. M. Keenan (F '36) formerly general sales manager, Pennsylvania Power and Light Company, Allentown, has been appointed chief engineer. Mr. Keenan entered the engineering field as a student apprentice with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., after his graduation from Purdue University in 1913. In 1915 he went to work for the Merchants' Heat and Light Company, Indianapolis, Ind., as repairman, subsequently rising to the position of superintendent of power, but he returned to the Westinghouse Company in 1916. In 1917 he became a test engineer, the Union Gas and Electric Company, St. Louis, Mo., and then superintendent of power, Little Rock (Ark.) Railway and Electric Company. Mr. Keenan became associated with the Lehigh Navigation Electric Company, Allentown, Pa., which was merged with the Pennsylvania Power and Light Company, in 1918. He assumes his duties as chief engineer after more than two years with the War Production Board, Washington, D. C., in connection with electric-power supply.

J. T. Kimball (A '18) electrical engineer, Niagara Hudson Power Corporation, Buffalo, N. Y., has been elected a vice-president and director of the New York Power and Light Corporation and a vice-president of the Central New York Power Corporation, Syracuse. He will continue to act as consultant for the companies in the western division of the Niagara Hudson system. Mr. Kimball was graduated from the University of Wisconsin in 1914 and then entered the employ of the Bell Telephone Company, Chicago, Ill. From 1916 until 1918 he was on the engineering staff of the Wisconsin Railroad Commission, Madison, and in 1918 he entered the firm of Ford, Bacon, and Davis, consulting engineers, New York, N. Y. He stayed with this company until 1932 when he became a rate and valuation engineer for the Niagara Hudson Power Corporation.

O. B. Blackwell (A '08, F '17) formerly vice-president, Bell Telephone Laboratories, Inc., New York, N. Y., has been elected to the board of directors of that company and on October 1, 1944, was appointed an assistant vice-president, American Telephone and Telegraph Company, New York. Mr. Blackwell was graduated from the Massachusetts Institute of Technology in 1906 and in the same year entered the engineering department of the American Telephone and Telegraph Company, becoming transmission and protection engineer in 1914. In 1919 he was made transmission development engineer, and when that department was transferred to the Bell Telephone Laboratories in 1934 he became director of transmission development. Mr. Blackwell was appointed manager of staff departments in 1935 and in 1936 was elected vice-president.

J. B. Harris, Jr. (A '17) vice-president, Rumsey Electric Company, Philadelphia, Pa., has been elected president of that company. After his graduation from the Bliss Electrical School in 1911, Mr. Harris was connected with the General Electric Company and the Westinghouse Electric and Manufacturing Company. He was employed as sales engineer by the Pittsburgh (Pa.) Transformer Company in 1917 and in 1920 was a member of the firm of Harris and Evans, Philadelphia, Pa., which became the firm of Harris and Butler in 1923. Mr. Harris was made president of the latter firm in 1925 and continued in that position until 1935 when he was appointed manager of the electrical-equipment department, Rumsey Electric Company. He became vice-president in 1939.

Deveraux Martin (M '43) formerly chief radio engineer, the J. H. Bunnell Company, Brooklyn, N. Y., has been appointed chief engineer, the Wilcox-Gay Corporation, Charlotte, Mich. Mr. Martin is a graduate of the Massachusetts Institute of Technology (1929). He was with the Westinghouse Electric and Manufacturing Company, Chicopee Falls, Mass., from 1929 until 1931 as development engineer, and then he entered the employ of the De Forest Radio Company, Passaic, N. J. After a period of five years during which he managed his own business, the Martin Radio Laboratory, Newcastle, Me., Mr. Martin was employed by the Radio Receptor Company, New York, N. Y. (1937) and the Federal Telegraph Company, Newark, N. J. He joined the J. H. Bunnell Company in 1942.

J. S. Morgan (A '39) switchgear division, Allis-Chalmers Manufacturing Company, Milwaukee, Wis., has been appointed sales engineer-in-charge of switchgear sales. **W. M. Picksley** (A '31, M '40) assistant engineer, has been appointed assistant engineer-in-charge of the control section of the electrical department of the Allis-Chalmers Company.

OBITUARY

Frank Anderson Merrick (A '07) vice-chairman of the board of directors, Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa., died October 26, 1944. Mr. Merrick was born in Pennsylvania in 1868 and was graduated from Lehigh University in 1891. After his graduation he became an apprentice at the Thomson-Houston Electric Company, Lynn, Mass., and by 1892 had advanced to factory construction inspection. He joined the firm of Blood and Hale, consulting engineers, Boston, Mass., in 1897 and in 1898 became manager and chief engineer of the Steel Motor Company, Johnstown, Pa., a subsidiary of the Lorain Steel Company. When the Westinghouse Electric and Manufacturing Company acquired the electrical branch of the company, Mr. Merrick was transferred to the Westinghouse plant at East Pittsburgh, Pa. In 1903 he supervised the building of the plant at Hamilton, Ontario, Canada, and became its manager of works, progressing to vice-president and general manager of the Canadian Westinghouse Company, Ltd. During the first World War he took charge of the Chicopee Falls, Mass., factory and after the war was sent to England as special representative of the Westinghouse Electric International Company. In 1921 he reassumed his duties in Hamilton, Ontario, and in 1925 he was made vice-president and general manager of the company's offices at East Pittsburgh. Mr. Merrick became president of the company in 1929 and vice-chairman of the board in 1938.

John H. Gardner (A '25, M '34) brigadier general, United States Army, Washington, D. C., died October 11, 1944. General Gardner was born in Meadowdale, N. Y., on October 10, 1893, and was a graduate of Union College with a bachelor-of-science degree. He also held a master-of-science degree in electrical engineering from Union College (1915) and a master-of-science degree in communication engineering from Yale University (1925). General Gardner was associated with the General Electric Company in Schenectady, N. Y., and Chicago, Ill., from 1913 to 1916. When the United States entered the first World War in 1917 he was commissioned a second lieutenant in the Army and was with the American forces in occupied Germany until 1920. In 1921 he returned to the United States as a captain in the Signal Corps, and in 1943 he was promoted to the rank of brigadier general with command of the Signal Corps Aircraft Signal Service, Wright Field, Dayton, Ohio. General Gardner was transferred to Washington in August 1943 as assistant chief of the Procurement and Distribution Service.

Norman Short Braden (A '09, M '20) vice-chairman of the board, Canadian Westinghouse Company, Ltd., Hamilton, Ontario, Canada, died September 27, 1944. Mr. Braden was born on June 15, 1869, in Indianapolis, Indiana. His first position was as an apprentice in the shop of the Jenney Electric Company in 1892, and in 1894 he became construction and sales engineer. In 1899 he joined the Westinghouse Electric and Manufacturing Company, Cleveland, Ohio, as sales engineer, rising to district manager in 1903. He was transferred to the Canadian Westinghouse Company in 1904 as manager of the sales department, and was appointed third vice-president in 1919, member of the board of directors in 1926, and vice-chairman of the board of directors in 1939. Mr. Braden retired from active service this year but remained vice-chairman. He was a member of the Engineering Institute of Canada.

Cornelius Edmond O'Donnell (A '32) field supervisor, operating department, Central Illinois Public Service Company, Mattoon, died October 3, 1944. Born in Rantoul, Ill., on September 10, 1899, Mr. O'Donnell was graduated from the University of Illinois in 1930 with the degree of bachelor of science in electrical engineering. In July of the same year he started the student engineering course of the Westinghouse Electric and Manufacturing Company, in October he went to work on the test floor of the company at East Pittsburgh, Pa., and in 1931 he entered the supply engineering department laboratory. Mr. O'Donnell joined the Central Illinois Public Service Company in 1935 as distribution clerk and was made field supervisor in 1940.

Louis Washington Pratt (A '38) assistant engineer, municipal department, Hydro-Electric Power Commission of Ontario, Toronto, Canada, died October 3, 1944. Mr. Pratt was born in London, England, on April 25, 1877. In 1896 he was employed by the Brantford (Ontario) Electric and Operating Company, Ltd. Subsequently, he was with the Western Counties Electric Company, Ltd., Brantford (1905), and the Federal Electrical Construction Company, Ltd., Toronto (1906). In 1907 Mr. Pratt joined the Dominion Power and Transmission Company, Ltd., Hamilton, Ontario, where he stayed until 1932 when he entered the employ of the Hydro-Electric Power Commission.

Henry Escher, Jr. (A '37) lieutenant in the Armed Forces of the United States and formerly of the industrial department, aviation division, General Electric Company, Schenectady, N. Y., was killed in action in June 16, 1944. Lieutenant Escher was born on July 1, 1913, in Brooklyn, N. Y., and is a graduate of Princeton University, Princeton, N. J., (1934). From 1934 to 1936 he was an assistant instructor at Princeton University, where he taught laboratory classes in introductory electrical engineering. He joined the General Electric Company, Bloomfield, N. J., as a student engineer in 1936 and was employed in the Schenectady plant when he entered the armed services this year.

Ernest Oswald Stockman (A '39) lieutenant commander, Royal Canadian Naval Volunteers Reserve, formerly resident naval engineer overseer, Halifax Shipyards, Dartmouth, Nova Scotia, Canada, has been reported missing in action. Born in Newcastle-on-Tyne, England, on May 28, 1908, Commander Stockman attended Rutherford College. He was employed by C. A. Parsons and Company, Ltd., Newcastle-on-Tyne in various engineering capacities from 1923 until 1934 when he became sales engineer in the Canadian office of the C. A. Parsons Company, Toronto, Ontario. Commander Stockman received his commission in the RCNVR in 1941.

Carlyle J. Roberts (A '22) chief inspector, Leeds and Northrup Company, Philadelphia, Pa., died June 26, 1944. Mr. Roberts was born on January 26, 1897, in Granville, Ohio. He was a graduate of Denison University with a bachelor-of-science degree in physics and has been with the Leeds and Northrup Company since 1918 when he was placed in charge of laboratory standards and equipment.

Leo Behr (A '29) research department, Leeds and Northrup Company, Philadelphia, Pa., died June 25, 1944. He was born in New York, N. Y., in 1898 and was the recipient of both the degree of mechanical engineering and the degree of doctor of philosophy from Cornell University. Doctor Behr became associated with the Leeds and Northrup Company in 1917 in the development department.

MEMBERSHIP

Recommended for Transfer

The board of examiners, at its meeting on November 16, 1944, recommended the following members for transfer to the grade of membership indicated. Any objections to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Danner, R. F., general supt., Oklahoma Gas & Elec. Co., Oklahoma City, Okla.
Gross, I. W., electrical research engr., American Gas & Electric Service Corp., New York

2 to grade of Fellow

To Grade of Member

Askey, J. S., section engr., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Brownlee, T., lightning arrester research & development, General Elec. Co., Pittsfield, Mass.
Chisholm, H. E., asst. engr. of equipment, Bell Tel. Co. of Pa., Pittsburgh, Pa.
Church, E. A., engr., Boston Edison Co., Boston, Mass.
Crandell, C. F., member, technical staff, Bell Tel. Labs., New York
Crawford, C. S., plant engr., Charity Hospital of Louisiana, New Orleans, La.
Eardley, M. V., senior elec. engr., Dept. of Water & Power, Los Angeles, Calif.
Freundt, G. L., elec. engr., Sievert Elec. Co. Inc., Chicago, Ill.
Gille, W. H., chief engr., Aero Div., Minneapolis-Honeywell Regulator Co., Minneapolis, Minn.
Goodale, E. C., elec. engr., Bonneville Power Adm., Portland, Ore.
Harvey, R. H., general mgr. and chief engr., Companhia Carris de Ferro de Lisboa, Lisboa, Portugal
Kahn, Frank, senior technical asst., Philadelphia Elec. Co., Philadelphia, Pa.
Kap, F. W., elec. engr., Sanitary Dist. of Chicago, Chicago, Ill.
Keever, L. M., associate prof. of E.E., North Carolina State College, Raleigh, N. C.
Meier, Otto, asst. prof. of E.E., Duke Univ., Durham, N. C.
Moore, Paul, assoc. elec. engr., Public Works Dept., Navy Yard, Mare Island, Calif.
Mostrom, John, elec. engr., Phillips Petroleum Co., Bartlesville, Okla.
Parker, R. S., industrial engr., War Dept., Huntsville, Ala.
Payne, R. B., senior engr., War Production Board, Washington, D. C.
Quinlan, A. L., engr., Western Elec. Co., Chicago, Ill.
Rhoton, W. O., elec. engr., Delco-Remy Div., General Motors Corp., Anderson, Ind.
Schille, C. A., head, elec. engr., Industrial Engg. Div., Giffels & Vallet, Inc., Detroit, Mich.
Sigman, F. L., chief engr., Buffalo Elec. Co. Inc., Buffalo, N. Y.
Spaulding, A. M., plant assignment supervisor, Mountain States Tel. & Tel. Co., Denver, Colo.
Svendsen, O. P., president & treasurer, Boustead Elec. & Mfg. Co., Minneapolis, Minn.

Thomas, E. U., elec. engr., Specialties, Inc., Locust Valley, L. I.
Thomas, E. J., engr., General Elec. Co., Fort Wayne, Ind.
Walsh, F. R., president, Electric Switchboard Co., New York
White, J. E., engr., Westinghouse E. & M. Co., Bloomfield, N. J.
Williams, L. T., acting chief engr., Southwestern Gas & Elec. Co., Shreveport, La.

30 to grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Any member objecting to the election of any of these candidates should so inform the national secretary before December 30, 1944, or February 28, 1945, if the applicant resides outside of the United States or Canada.

To Grade of Member

Adams, E. C., Gulf States Util. Co., Beaumont, Texas
Calvo, D., E., Nat. Univ. of Colombia, Bogota, Col., S. A.
Cavagnet, L. J., Cons. Tel. & Elect. Subway Co., New York, N. Y.
Cole, I. V. (Reelection), Lexington Elec. Prod. Co., Lexington, Ky.
Crosman, W. T., Duquesne Lt. Co., Pittsburgh, Pa.
Dudrear, A. C. (Reelection), I. B. Abel & Son, York, Pa.
Fife, W. H. (Reelection), Austin Engg. Co., East Cleveland, Ohio
Freeman, N. R. (Reelection), Amer. Loco. Co., Schenectady, N. Y.
Gauggel, H. J. W., Gen. Elec. Co., Atlanta, Ga.
Gelder, W. A. E., Elect. Lt. Cmdr., R. N. V. R., Grimsby, England
Gunckel, W. J., Rural Elect. Admin., St. Louis, Mo.
Hannah, S. W., Rocky Mountain Arsenal, Denver, Colo.
Heffelman, M. C. (Reelection), N. Mex. Pr. Co., Santa Fe, N. Mex.
Heinz, W. B., Cons. Engr., Bound Brook, N. J.
Huppert, W. (Reelection), H. Goodman & Sons, Inc., New York, N. Y.
Hutchinson, C. G., Engg. Labs., Inc., Tulsa, Okla.
James, A. J. T., Hackbridge Elec. Const. Co., Ltd., Walton-on-Thames, England
Kelly, H. A., Wheeling Stamping Co., Wheeling, West Va.
Korn, F. A. (Reelection), Bell Tel. Lab., Inc., New York, N. Y.
Krueger, H. H. (Reelection), Utah Pr. & Lt. Co., Salt Lake City, Utah
Leonard, E. M. (Reelection), Allis-Chalmers Mfg. Co., Pittsburgh, Pa.
Lopez, J. J., Amer. Tel. & Tel. Co., Albuquerque, N. Mex.
Lovfald, P., Cons. Engr., New York, N. Y.
Mahoney, J. H., Boston Edison Co., Boston, Mass.
Markers, H. W. (Reelection), Commonwealth Edison Co., Chicago, Ill.
McCrocklin, A. J., Jr., Dow Chem. Co., Freeport, Texas
Mead, S. N., Henschel Corp., Amesbury, Mass.
Miller, H. C., Alan Wood Steel Co., Conshohocken, Pa.
Mollo, G. A., Koppers Co., Inc., Pittsburgh, Pa.
Munro, J. C., B. C. Elec. Ry. Co., Ltd., Vancouver, B. C., Can.
Pennell, C. E., N. J. Bell Tel. Co., Newark, N. J.
Pentland, L., Combined Prod. & Res. Board, Washington, D. C.
Perry, A., Norwich Corp., Norwich, England
Persons, J. T. (Reelection), Cen. Pr. & Lt. Co., Corpus Christi, Texas
Post, J. V., Gulf States Util. Co., Navasota, Texas
Reiss, M. O., Elec. Zinc Co. of A'Asia, Ltd., Hobart, Tasmania
Rieman, E. F., Okonite Co., Passaic, N. J.
Schley, W. H., Dallas Pr. & Lt. Co., Dallas, Texas
Seaholm, W. E., Acting City Manager, Austin, Texas
Shanely, F. D., Lear, Inc., Piqua, Ohio
Steven-Hubbard, N., Cadet, OCTU, East Africa Command
Taylor, J. L., Mid-Lincolnshire Elec. Sup. Co., Ltd., Grantham, England
Turner, J. G. (Reelection), U. S. Bur. of Reclamation, Denver, Colo.
Walter, G. F. (Reelection), Pub. Serv. Elec. & Gas Co., Maplewood, N. J.
Wells, H. J., Stone & Webster, Oak Ridge, Tenn.
Witherspoon, J. (Reelection), Gen. Elec. Co., Schenectady, N. Y.
Zobel, A. E., Tenn. Eastman Corp., Oak Ridge, Tenn.

47 to grade of Member

To Grade of Associate

United States and Canada

1. Northeastern

Belluscio, F. J., Taylor Inst. Co., Rochester, N. Y.
Brown, H. A., Walsh Kaiser Co., Providence, R. I.
Brown, H. R., Jr., Gen. Elec. Co., Schenectady, N. Y.
Buck, F. W., United Illum. Co., New Haven, Conn.
Butz, A. N., Jr., Harv. Underwater Sound Lab., Cambridge, Mass.
Conway, G. J., Gen. Elec. Co., Buffalo, N. Y.
Cottrell, C. L., Cornell Univ., Ithaca, N. Y.
Dautrich, G. U., Gen. Elec. Co., Hartford, Conn.
Ellsworth, I. W., Westinghouse Elec. & Mfg. Co., Boston, Mass.
Farrar, R. O., Westinghouse Elec. & Mfg. Co., Boston, Mass.
Fisher, J. C., Harvard Engg. School, Cambridge, Mass.
Jenkins, W. C., Westinghouse Elec. & Mfg. Co., Syracuse, N. Y.
Kappauf, E. F., Ensign, USNR, Boston, Mass.
McHugh, H. R., Kennecott Wire & Cable Co., Phillipsdale, R. I.
Miller, J. C., N. Y. State Elec. & Gas Corp., Lockport, N. Y.
Waynick, A. H., Harvard Univ. Cambridge, Mass.
Weiss, H. E. (Reelection), Allis-Chalmers Mfg. Co., Buffalo, N. Y.
Wood, M. L., Curtiss-Wright Corp., Buffalo, N. Y.

2. Middle Eastern

Ackermann, R. W., Amer. Tel. & Tel. Co., Cleveland, Ohio
Andrews, D. E., Master Elec. Co., Dayton, Ohio
Attwood, S. H., Master Elec. Co., Dayton, Ohio
Bova, N. J., Master Elec. Co., Dayton, Ohio
Boyd, R. C., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Campbell, F. S., Hartford Steam Boiler Insp. & Ins. Co., Philadelphia, Pa.
Carle, J. H., Carle Elec. Const. Co., Akron, Ohio
Carver, D. W. (Reelection), Master Elec. Co., Dayton, Ohio
Crockett, J. W., Graybar-Elec. Co., Inc., Baltimore, Md.
Davis, R. E., A. T. S. C., Wright Field, Dayton, Ohio
DuBroff, W. C., Captain, U. S. Army, Wright Field, Dayton, Ohio
George, A. B., Wilbur Watson &Assoc., Cleveland, Ohio
Gilchrist, A. D., Leece-Neville Co., Cleveland, Ohio
Gray, M. H., A.T.S.C., Wright Field, Dayton, Ohio
Hanson, P. L., Ideal Elec. & Mfg. Co., Mansfield, Ohio
Harris, M., Nat. Elec. Coil Co., Bluefield, W. Va.
Harry, J. N., Wright Field, Dayton, Ohio
Haynes, C. H., Bird Engg. Co., Cleveland, Ohio
Hertz, H. F. (Reelection), Phila. Elec. Co., Philadelphia, Pa.
Hughes, R. E., National Elec. Coil Co., Bluefield, W. Va.
Hunt, W. A., Radio Station WHIZ, Zanesville, Ohio
Kraus, R., Cudahy Packing Co., Philadelphia, Pa.
Lang, J. S., Auto. Temp. Cont. Co., Philadelphia, Pa.
Livermore, E. H., Jr., Del. Pr. & Lt. Co., Wilmington, Del.
MacCauley, T. H., Gen. Elec. Co., Philadelphia, Pa.
Nordfelt, H. C., Cont. Sales & Engg. Co., Pittsburgh, Pa.
Oppermann, R. H. (Reelection), Assoc. Fact. Mut. Fire Ins. Cos., Philadelphia, Pa.
Poeschl, J. J., Atlantic Ref. Co., Philadelphia, Pa.
Price, S., Electric Cont. & Mfg. Co., Cleveland, Ohio
Starbuck, H. S., Gen. Motors Corp., Dayton, Ohio
Strahle, P. J., Leece-Neville Co., Cleveland, Ohio
Taylor, L. M., Bureau of Ships, Washington, D. C.
Trautman, D. L., Jr., Carnegie Inst. of Tech., Pittsburgh, Pa.
Wolfe, K., Leece-Neville Co., Cleveland, Ohio
Wollerton, C. E., Gen. Elec. Co., Philadelphia, Pa.

3. New York City

Alden, A., York & Sawyer, New York, N. Y.
Backer, H. N. T. Univ., New York, N. Y.
Bolles, H. J., Weston Elec. Inst. Corp., Newark, N. J.
Di Toro, M. J. (Reelection), Hazeltine Corp., Little Neck, N. Y.
Judkins, R. P., Lieut. (jg), USNR, New York, N. Y.
Lacher, K. K., Westinghouse Elec. & Mfg. Co., New York, N. Y.
Laestadius, J. E., Columbia Univ., New York, N. Y.
Larys, B., Diehl Mfg. Co., Finderne, N. J.
Marino, L., Radio Corp. of America, Harrison, N. J.
Martinez-Feralta, A., Fed. Tel. & Radio Corp., East Newark, N. J.
Maynard, M. J., Horni Signal Co., New York, N. Y.
Morse, H. D., George G. Sharp, New York, N. Y.
Murphy, F. A., Ward Leonard Elec. Co., New York, N. Y.
O'Brien, J. P., Anaconda Copper Min. Co., New York, N. Y.
Poehler, H. A., Int'l. Elec. Labs., New York, N. Y.
Quintana, C. H. M., Bell Tel. Lab., Inc., New York, N. Y.
Rick, F. L., Jersey Central Pr. & Lt. Co., Allenhurst, N. J.
Shumaker, H. A., Diehl Mfg. Co., Somerville, N. J.
Smith, F. T. (Reelection), Diehl Mfg. Co., Finderne, N. J.
Tooie, L. J., Gen. Cable Corp., Bayonne, N. J.
Torcivia, J. A., Westinghouse Elec. & Mfg. Co., Newark, N. J.
Tracy, W. A., Bell Tel. Lab., Inc., New York, N. Y.
Whitman, H. M., Diehl Mfg. Co., Somerville, N. J.
Wieland, G. J., Jr., Bell Tel. Lab., Inc., New York, N. Y.

4. Southern

Balfour, H. B., Jr., La. Pr. & Lt. Co., West Monroe, La.
Becker, W. N., Clinton Engineer Works, Oak Ridge, Tenn.
Boch, A. L., Clinton Engineer Works, Oak Ridge, Tenn.
Cato, S. G., Memphis Lt. Gas & Water Div., Memphis, Tenn.
Drake, R. S., Chattanooga Elec. Pr. Board, Chattanooga, Tenn.
Greenberg, E. E. (Reelection), Kelley-Koett Mfg. Co., Covington, Ky.
Holland, J. T. (Reelection), Duke Pr. Co., Charlotte, N. C.
Mosso, A. J., Tennessee Eastman Corp., Oak Ridge, Tenn.
Sauer, C. M., Louis. Gas & Elec. Co., Louisville, Ky.
Smith, T. G., Allis-Chalmers Mfg. Co., New Orleans, La.
Thompson, E. H., Southern Bell Tel. & Tel. Co., New Orleans, La.
Walker, W. E., Gen. Elec. Co., Atlanta, Ga.

5. Great Lakes

Audier, M., Cutler-Hammer, Inc., Milwaukee, Wis.
Barta, W. J., Amer. Bur. of Shipping, Detroit, Mich.
Clement, M. A., Automatic Elec. Co., Chicago, Ill.
Dodd, C. M., Iowa State Col., Ames, Iowa
Glass, P., Askania Reg. Co., Chicago, Ill.
Harrison, D. L., Allen Bradley Co., Milwaukee, Wis.
Holmes, R. H., Minn. Pr. & Lt. Co., Duluth, Minn.
Jacobsen, T. H., Delta-Star Elec. Co., Chicago, Ill.
Janustko, E. J., Henry Ford Trade School, Dearborn, Mich.
Koerwitz, N. A., Board of Pub. Works, Niles, Mich.
Potter, L. B., Detroit Edison Co., Detroit, Mich.
Sancomb, C., Allis-Chalmers Mfg. Co., West Allis, Wis.
Schotz, A., Cutler-Hammer, Inc., Milwaukee, Wis.
Spellmire, G. W., Gen. Elec. Co., Chicago, Ill.
Stong, K. K., Allen-Bradley Co., Milwaukee, Wis.

6. North Central

Abrams, M. L., U. S. Bur. of Rec., Denver, Colo.

7. South West

Bartosh, F. A., Emerson Elec. Mfg., St. Louis, Mo.
Bates, J. L., Cen. Pr. & Lt. Co., Corpus Christi, Texas
Dugan, J. M., Gulf States Util. Co., Port Arthur, Texas
Figari, E. E., Gulf States Util. Co., Beaumont, Texas
Finley, R. A., Texas Elec. Serv. Co., Fort Worth, Texas
Groh, W. J., Cent. Kans. Elec. Coop. Assoc., Inc., Great Bend, Kans.
Lowery, J. M., Curtiss-Wright Corp., Robertson, Mo.
McCoppin, J. T., Gulf States Util. Co., Beaumont, Texas
McFarland, O. C. (Reelection), S. W. Bell Tel. Co., Kansas City, Mo.
Morton, R. E., Gulf States Util. Co., Navasota, Texas
Olive, W. W., Jr., Curtiss-Wright Corp., St. Louis, Mo.
Sims, V. R., Emerson Elec. Mfg. Co., St. Louis, Mo.
Walling, F. E., Cons. Steel Corp., Ltd., Orange, Texas
Walston, T. E., Jr., Cons. Steel Corp., Ltd., Orange, Texas
Wynn, T. C., Lower Colo. River Auth., Austin, Texas

8. Pacific

Cates, W. K., Westinghouse Elec. & Mfg. Co., Sacramento, Calif.
Catton, J. A., Lockheed Aircraft Corp., Burbank, Calif.
Chaika, S., Lieut. (jg), USNR, San Francisco, Calif.
Glazunov, S. V., C. C. Moore & Co., San Francisco, Calif.
Kemp, C. A., U. S. Navy Yard, Mare Island, Calif.
Larimore, J. F., A. W. Earl, Cons. Engr., San Francisco, Calif.
Main, H. E., North Amer. Avia., Inc., Inglewood, Calif.
Montroy, F. E., Montroy Elec. Mfg. Co., Los Angeles, Calif.
Stephens, H. R., South. Calif., Edison Co. Ltd., Chino, Calif.
Youngman, W. C., U. S. Navy Yard, Mare Island, Calif.

9. North West

Cerveny, J. P., Bonneville Pr. Adm., Portland, Oreg.
Hendrey, G. R., W. R. Hendrey Co., Seattle, Wash.
Howard, J. S., Alum. Co. of America, Trentwood, Wash.
Myrick, E. P., Mont. Pr. Co., Great Falls, Mont.
Palmer, L., Puget Sound Pr. & Lt. Co., Seattle, Wash.
Paschall, J. P., Portland Gen. Elec. Co., Portland, Oreg.
Ream, R. F., Gen. Elec. Co., Salt Lake City, Utah
Shearer, E. W., Bonneville Pr. Adm., Portland, Oreg.

10. Canada

Ferguson, N. H., Dominion Carbon Brush Co., Ltd., Toronto, Ont., Can.
Frarerson, J., Hydro-Elec. Pr. Comm. of Ont., Toronto, Ont. Can.
Paisley, P. P., Mica Co. of Can., Ltd., Hull, Que., Can.
Tickell, A. B., Ford Motor Co., Ltd., Windsor, Ont., Can.

Elsewhere

Carrion S., J., Com. Fed. de Elec., Patzcuaro, Mich. Mex.
de Albornoz, R. C., Serv. Com. Ind. S. A., Mexico, D. F., Mex.
Escobar B., J. V., Soc. Mex. de Credito Ind., S. A., Mexico, D. F., Mex.
Hernandez M., A., Fed. Com. of Elec., Mexico, D. F., Mex.
Lazcano R., L., Contractor & Cons. Engr., Coyoacan, D. F., Mex.
Letourneau, R., North. Elec. Co., Montreal, Que., Can.
Lira Z. E., Fed. Com. of Elec., Mexico, D. F., Mex.
Melgarejo P., A., Mex. Lt. & Pr. Co., Ltd., Mexico D. F., Mex.
Mora V., L., Cons. Engr., Mexico D. F., Mex.
O'Farril, C. C., Contractor, Mexico, D. F., Mex.
Parent, L. P., P. McCuaig, Ltd., Montreal, Que., Can.
Prakash, C., Stand. Tel. & Cables, London, England
Rowland, R. R., Johnson & Phillips Ltd., London, England
Ruiz V., J. L., Contractor, Mexico, D. F., Mex.
Strohbach, W. C., Cia Nac. de Elec., S. A., Torreon, Mex.
Sturgeon, J. R., Aircraft Ministry, Malvern, England
Toro Ochoa, H., Lt. & Pr. Co., Medellin, Col., S. A.
Van Ockeln, A. H., Southern Ry., Southampton, England
Watts, K. F., Govt. Rys., Sydney, Aust.

Total to grade of Associate
United States and Canada, 141
Elsewhere, 19

OF CURRENT INTEREST

Continuing Progress Reported at ECPD 12th Annual Meeting

In spite of continuing wartime difficulties, further progress was reported toward the general objectives of the Engineers Council for Professional Development, at the 12th annual meeting of council held in New York, N. Y., October 20–21, 1944. As stated by Chairman Everett S. Lee (F'30) in his report to the council for the year: "This has been another substantial year for ECPD. The personal contributions to the work in this period of difficulty have been outstanding." ECPD is a joint organization of eight national engineering societies, including AIEE, and its general objective is the enhancement of the professional status of the engineer. Its other constituent organizations are the American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, American Society of Mechanical Engineers, American Institute of Chemical Engineers, the Engineering Institute of Canada, Society for the Promotion of Engineering Education, and the National Council of State Boards of Engineering Examiners.

Development of a program for the accrediting of technical institutes is one of the outstanding achievements reported for the year. Patterned after the program of accrediting engineering-college curriculums that has proved so successful for some ten years, the new program for accrediting technical institutes will be administered by a subcommittee of the ECPD standing committee on engineering schools. The new subcommittee will be headed by Dean H. P. Hammond of Pennsylvania State College.

Approval of a revised general reading list for junior engineers was among other important actions taken by the council at this meeting, and publication of the list for general circulation was authorized. Progress also was reported toward completion of the manual for junior engineers that has been in process for some time.

Continuing progress of the measurement and guidance program of the committee on student selection and guidance was reported. There is an increase in the number of students being tested during the current year, and a year or two more will be required for completion of the project. The joint cooperative program between the ECPD and the Society for the Promotion of Engineering Education aimed at developing professional attitudes in students was carried forward during the year, many teachers expressing the opinion that the professional aspects of engineering should be brought into all courses.

Because the engineering schools still are operating under wartime programs, very few inspections of engineering curriculums were made during the year. However, plans are being made for reappraisal of all curriculums after the war. In previous years, this work has been considered one of the outstanding achievements of ECPD.

Further details pertaining to the aforementioned activities were presented in the annual reports of the four standing committees of ECPD. Several special committees reported on their work during the year, and the various society representatives presented their annual reports to the council. Details of these reports are given separately in this article.

Supplementing the business sessions, an evening dinner meeting was held at which the general question, "What is ahead in engineering education?" was discussed. This is discussed elsewhere in this item. Related to this discussion was an official action taken during one of the business sessions endorsing the SPEE report on engineering education after the war (*EE, Aug. '44, p. 319*).

Expenditures during the year totalled $11,927.72, and a budget totaling $14,471.23 was adopted for 1944–45. ECPD income is derived chiefly from contributions from the constituent societies (AIEE· $1,700 for 1944–45). For the past several years, these have been augmented by an annual contribution from Engineering Foundation, which has alloted $5,000 again for the ensuing year.

Officers and Committees for 1944–45

E. S. Lee (AIEE) engineer, General Electric Company, Schenectady, N. Y., was re-elected chairman, and James W. Parker (ASME) president, general manager, and director, The Detroit Edison Company, Detroit, Mich., vice-chairman. R. L. Sackett, assistant to the secretary, American Society of Mechanical Engineers, New York, N. Y., was named secretary, and George T. Seabury, secretary, American Society of Civil Engineers, New York, N. Y., assistant secretary.

In addition to these four officers, members of the executive committee for 1944–45 are:

George W. Burpee (ASCE), president, General Aniline and Film Corporation, New York, N. Y.; W. B. Plank (AIME), professor of mining, Lafayette College, Easton, Pa.; R. S. Goetzenberger (ASME), vice-president, Minneapolis-Honeywell Regulator Co., Philadelphia, Pa.; O. W. Eshbach (AIEE), dean, Northwestern Technological Institute, Northwestern University, Evanston, Ill.; S. D. Kirkpatrick (AIChE), editor, *Chemical and Metallurgical Engineering*, New York, N. Y.; D. B. Prentice (SPEE), president, Rose Polytechnic Institute, Terre Haute, Ind.; C. R. Young (EIC), dean, faculty of applied science and engineering, University of Toronto, Toronto, Ontario, Canada; C. C. Knipmeyer (NCBSEE), professor of electrical engineering, Rose Polytechnic Institute, Terre Haute, Ind.

The following representatives of ECPD member societies were announced for the 1944–47 term:

Reappointments—W. R. Chedsey (AIME), consulting engineer, Columbus, Ohio; J. W. Parker (ASME), president, general manager, director, The Detroit Edison Company, Detroit, Mich.; S. D. Kirkpatrick (AIChE), editor, *Chemical and Metallurgical Engineering*, New York, N. Y.

New appointments—S. C. Hollister (ASCE), dean of engineering, Cornell University, Ithaca, N. Y.; E. C. Stone (AIEE), vice-president and general manager, Duquesne Light Company, Pittsburgh, Pa.; H. S. Rogers (SPEE), president, Polytechnic Institute of Brooklyn, Brooklyn, N. Y.; C. J. Mackenzie (EIC), president, National Research Council, Ottawa, Ontario, Canada; Carl L. Svensen (NCSBEE), secretary, Texas Board of Registration for Professional Engineers, Austin, Texas.

Newly elected committee chairmen for 1944–45 are:

Committee on professional training, C. A. Pohl, consulting engineer, New York, N. Y.

Committee on professional recognition, N. W. Dougherty, dean of engineering, University of Tennessee.

Committee on information, George A. Stetson, editor, American Society of Mechanical Engineers, New York, N. Y.

The following committee chairmen were re-elected for the coming year:

Committee on student selection and guidance, A. R. Cullimore, president, Newark (N. J.) College of Engineering.

Committee on engineering schools, D. B. Prentice, president, Rose Polytechnic Institute, Terre Haute, Ind.

ECPD Committee Reports for 1943–44

Reports of its four standing committees were presented, reviewing progress during the year in the fields of student selection and guidance, engineering schools, professional training, and professional recognition. Six special committees also reported their activities. The following abstracts of these various reports give a cross section of the significant accomplishments of ECPD during the year.

STUDENT SELECTION AND GUIDANCE

The advisement, counseling, and guidance of students about to enter college, and the development of a battery of tests to aid in the proper selection of engineering students were the two projects with which the committee on student selection and guidance concerned itself during the year, reported A. R. Cullimore, chairman. Work on counseling has been carried on as formerly through a subcommittee whose members have interested themselves in contacting prospective engineering students, and in the distribution of "Engineering as a Career" and other material published by ECPD. The scope of this work has been extended considerably during the past year. More than 2,000 copies of "Engineering as a Career" were distributed to the Army through the Science Research Associates, and many were requested and distributed by the Veterans Administration. The committee envisions a great responsibility in connection with returning veterans and their advisement plans to extend this veterans' service greatly during the coming year.

During the first fiscal year of the measurement and guidance program being conducted jointly by the committee on selection and guidance and the Carnegie Foundation for the Advancement of Teaching 4,500 students were tested, involving the administration and interpretation of 27,000 separate tests. During the first two months of the second year, tests have been given to 3,150 students representing a total of 22,000 tests. Indications are that the number of students tested in the

second year will be considerably more than double the number handled in the first year. The major part of the financial support of this project is contributed by the Carnegie Foundation, only about eight to ten per cent of the cost being carried by ECPD. The continued and expanding interest of the Carnegie Foundation has carried the project into its second year and beyond the experimental stage, reported Chairman Cullimore.

It is planned to extend the services offered by the project to other institutions of reputable and recognized character, while retaining the original group for further study and research. It is believed that the tests will be extremely valuable also in connection with student selection and guidance of veterans. In September 1943, K. W. Vaughn director of the project, was appointed special consultant to the Army Specialized Training Division. The project has co-operated officially with the ASTD, completed several researches into the effectiveness of selection tests, and assisted in the editing of test materials and the preparation of official manuals for purposes of the ASTD. Since March, 1944, the project office has formally co-operated with the Veterans Administration through certain testing and guidance centers established at the Newark College of Engineering and the College of the City of New York.

ENGINEERING SCHOOLS

Development of a program for the accrediting of technical institutes was the most important accomplishment of the committee on engineering schools reported by chairman D. B. Prentice of that committee. The basis of accrediting the technical institutes is patterned after the procedure successfully followed for some years in accrediting engineering-college curriculums. The essential substance of the subcommittee's report already has appeared in *Electrical Engineering* (*July '44, pp 277–8*).

As announced in 1942, the committee on engineering schools has held its inspections of engineering-college curriculums to a minimum during the past two years. However, a few inspections were necessary in order to complete studies already begun or to prevent injustices to certain institutions. During the past year 13 curriculums at six institutions were investigated, and special consideration was given to eight curriculums at other institutions. The committee recommended to Council that the provisional accrediting of 31 curriculums at 16 schools be temporarily extended. The present status of the accrediting program, including the recommendations of the committee for 1944, is indicated in Table I. As in previous years, the committee gave consideration to a variety of miscellaneous matters that came to its attention.

PROFESSIONAL TRAINING

The activities of the committee on professional training during the past year have been devoted to advancing two projects which are aimed to be helpful to the younger engineer in his professional training, namely: revision of the reading list for junior engineers, and preparation of a manual for junior engineers. John C. Arnell was chairman of this committee during the year.

Recognizing that the existing reading list has continued without revision since it was issued originally in 1936, the junior committee of this committee has been engaged in revising the list and is considering other books recommended for inclusion. The junior committee has constantly kept in mind that the chief purpose of the list is to serve as an introduction to vast territories of human achievement and to stimulate the interest of the junior engineer in fields that may be explored with attendant cultural profit. As reported elsewhere, the revised list presented with the report of this committee was approved by the council for publication and distribution.

Further progress was reported on the manual for junior engineers which has been under development for some time. W. E. Wickenden (F '39) president, Case School of Applied Science, Cleveland, Ohio, who had accepted the authorship of the manual, reported to the committee that the material for the manual is about two thirds completed and the actual manuscript about one fourth complete. The committee plans to have the manual available for distribution in the postwar period when there will be a renewal of the more normal occupations of teacher, student, junior engineer, and employer.

PROFESSIONAL RECOGNITION

The ECPD committee on professional recognition directed its immediate efforts during the past year to the young engineer, particularly in the engineering schools, reported Chairman Charles F. Scott (HM '29). These efforts have been carried on jointly with a committee of the Society for the Promotion of Engineering Education in a plan for co-operative action announced last year. These co-operative activities have been directed to the engineering teacher "to arouse his responsibility in promoting the nontechnical phases of the make-up of the engineer and the qualities that contribute to the building of the profession."

Revision of the booklet, "The Second Mile," was carried out during the year under sponsorship of this committee, under the title "The Second Mile—a Resurvey." Some 20,000 copies of the original booklet were distributed. Doctor Scott reported that 30 per cent more copies of the new booklet had been sold in the first few months after it was issued than were sold in two years of the earlier edition.

REPORTS OF SPECIAL COMMITTEES

Progress regarding the proposed canons of ethics for engineers has been very slow during the past year, reported Chairman D. C. Jackson (F '12) of the committee on principles of engineering ethics. Three societies have approved the canons in their present form, some have offered suggestions for revisions, and others so far have reported no action. An article outlining the history and present status of the canons by Chairman Jackson appears elsewhere in this issue.

No committee action was reported by the committee on employment conditions for engineers, but Chairman Van Tuyl Boughton presented a report summarizing actions taken in this field by ECPD constituent societies. He reported that up to July 15, 1944, 30 of the 64 local sections of the American Society of Civil Engineers had amended their constitutions to provide for establishing collective-bargaining units, five had rejected the proposal by vote of section members, and in five the board of direction had decided not to submit the proposed plan to vote. Actual organization of the collective-bargaining committees was reported as slow.

The committee on information carried on its usual activities during the year, according to Chairman Stephen L. Tyler. Two general releases were issued, one pertaining to new officers and committee chairmen, and the other to the accrediting of technical-institute curriculums. The committee also issued the annual report for 1942–43 and co-operated with other committees in issuing other material.

A special committee presented a proposed procedure for the guidance of the council in accepting contributions that might be offered by individuals or groups other than the participating bodies in support of the work of ECPD; this procedure was adopted. It

Table I. Status of All Curriculums Submitted for Accrediting as of October 20, 1944

Curricula	Total Curriculums Submitted	Fully Accredited	Provisionally Accredited	Not Accredited	Action Pending or Deferred	Accredited Curriculums Discontinued	Options Under Accredited Curriculums
Aeronautical engineering	17	14	0	2	1	0	26
Agricultural engineering	11	3	0	8	0	0	1
Architectural engineering	18	13	1	3	0	1	2
Ceramic engineering	10	9	1	0	0	0	0
Chemical engineering	88	42	11	35	0	0	0
Civil engineering*	137	107	20	10	0	0	0
Electrical and communication engineering	133	108	18	7	0	0	0
Electrochemical engineering	2	0	0	0	0	2	0
Fuel technology	1	0	1	0	0	0	1
General engineering	14	8	0	5	1	0	0
Industrial engineering	24	21	0	3	0	0	10
Mechanical engineering	123	102	15	6	0	0	0
Metallurgical engineering	31	27	2	2	0	0	7
Mining (and geological) engineering	42	26	6	9	0	1	0
Naval architecture and marine engineering	3	3	0	0	0	0	1
Petroleum engineering**	17	11	3	2	0	1	6
Sanitary (and public-health) engineering	5	5	0	0	0	0	23
Others (specialized)	7	0	0	7	0	0	0
Total	683	499	78	99	2	5	—

* Includes building engineering and construction, engineering mechanics, and transport engineering.

** Includes petroleum and natural-gas engineering and petroleum refining.

authorizes the ECPD chairman, subject to the approval of the executive committee in each instance, to solicit from sources other than the participating bodies such funds as may be necessary or desirable for the furtherance of the general objectives or specific projects of ECPD.

Upon recommendation of a special committee on rules of procedure–representation, C. C. Williams, chairman, an amendment to the rules of procedure was adopted limiting membership in standing committees to two terms (of three years each) unless the council in session by vote of two thirds of the representatives present authorizes additional terms. The rules formerly stipulated that members should not serve more than two *consecutive* terms.

To consider specific requests for representation on the council by the Institute of Ceramic Engineers and the Institute of Radio Engineers, a special committee on representation had been appointed. The following recommendations, resulting from a study of the general society relationships in ECPD by that committee, were presented by Chairman W. B. Plank:

1. Until the Joint Conference of the Engineering Societies determines the conditions of association in professional matters with other engineering societies, the ECPD would be unwise to make any move in that direction.

2. Before any additional engineering society be invited into participation in the ECPD, if the field of that society be related to the field of any existing participating society, then the matter be referred to that participating society for its approval.

3. The committee on engineering schools should see that on each delegatory committee there is at least one qualified representative of each curriculum to be considered for accrediting.

4. All national engineering societies in the United States and Canada should be placed on the mailing list to receive ECPD reports and other literature.

Postwar Education Discussed at Dinner

For the second consecutive year, the discussions at the ECPD annual dinner centered around engineering education after the war. The principal address on this subject was delivered by George Granger Brown, chairman, department of chemical and metallurgical engineering, University of Michigan, and one of the ECPD representatives from the American Institute of Chemical Engineers. Three other viewpoints on the subject were presented in scheduled discussions by Dean C. R. Young of the University of Toronto; George W. Burpee, consulting engineer, Coverdale and Colpitts, New York, N. Y.; and Colonel C. E. Davies, secretary, American Society of Mechanical Engineers. ECPD Chairman Everett S. Lee acted as toastmaster.

Declaring that what is ahead is whatever we make it, Doctor Brown outlined five goals for engineering education in the future:

1. An understanding of the scientific principles and facts upon which the profession is based.

2. A facility in thinking and expression.

3. An appreciation of and skill in the experimental method as a means of finding the truth.

4. Sound principles of honesty, fairness, and the democratic spirit, with appreciation of the human and economic problems of modern society.

5. The beginnings of a philosophy and integration of skills in using the materials and energy of nature for the benefit of mankind.

Emphasizing that teachers of engineering are faced with an unprecedented opportunity and responsibility in the postwar period, Doctor Brown predicted that veterans are more likely to seek engineering education after the war than liberal education. For this reason, accelerated programs probably will have to be continued in engineering schools for at least two years after victory.

In presenting the Canadian viewpoint, Dean Young agreed that the majority of students after the war will want training in the sciences. Characterizing physicists as being concerned with the laws of nature and engineers with the needs of man, he urged that the colleges first provide education in the vocations and later liberal education at an adult level.

In presenting industry's viewpoint, Mr. Burpee said that industry will provide the specialized courses required by returning veterans. These will be a combination of work and training to broaden cultural interests and prepare the engineer for leadership. Mr. Burpee urged that the colleges teach a student how to make best use of his talents and give him an inspiration to go out after graduation and "make his place in the sun."

Educational functions and professional responsibilities are closely linked, stated Colonel Davies in discussing the societies' viewpoint. He declared that the societies have a responsibility in encouraging youngsters who have the capacity to grow to develop their qualities of leadership. He declared that ECPD is facing a greater opportunity than ever before to further its objectives in the postwar period.

Report of AIEE Representatives

"ECPD was able to render a novel service to the Institute during the past year," stated O. W. Eshbach, who presented the annual report of AIEE representatives to ECPD at the meeting of the council. "The board of examiners asked us to determine whether Melbourne University (Australia) came within the usual interpretation in this country of a school of recognized standing. The inquiry arose as a result of a request for enrollment of a number of students from Melbourne University, and the Institute's bylaws specify that students may be enrolled only from schools of recognized standing. We transmitted the inquiry to the chairman of ECPD's committee on engineering schools who was good enough to investigate and who was able to inform us that the engineering-degree students in good standing at the University of Melbourne would qualify for student membership in the Institute. We were happy to be able to transmit this finding to the board of examiners.

"During the year the Sections committee and the committee on Student Branches brought to the attention of the chairmen of the Sections and Branches both the ECPD pamphlet, "Will You Help?" and Chairman Lee's paper, "The Engineer in the Postwar World" (*EE, June '44, pp 278–20*). These were transmitted by special letter urging the distribution and the use of this material cooperatively with the sections and branches of the other engineering societies in carrying out locally the general objectives of ECPD.

"On page 301 of the August 1944 issue of *Electrical Engineering* will be found a report of Mr. Lee's appearance at the delegates' conference during the summer technical meeting in St. Louis, Mo., where he expanded on the theme, "Will You Help?"

During the year, and upon the recommendation of the chairman of the committee on Student Branches, the Institute purchased 5,000 copies of the revised pamphlet by W. E. Wickenden "The Second Mile—A Resurvey."

WAR PROGRAM . .

Aircraft Gunsight Extends Firing Range and Accuracy

An electronic gunsight of greater accuracy and less complexity of operation than the mechanical type previously used recently was installed on United States bombers. The gunsight was described by Erwin Hale, engineer of the Fairchild Camera and Instrument Corporation and coinventer with Irving Doyle of the improved gunsight, at the national fall meeting of the Institute of the Aeronautical Sciences in Dayton, Ohio.

The new gunsight, designated as the *K*-8 by the Army, has demonstrated an accuracy against the enemy's fastest airplanes approaching that of stationary guns firing at stationary targets. The device has extended the range of the 50-caliber machine gun to more than 1,000 yards in contrast to its former range of 400 to 600 yards. Even over this increased range a much higher accuracy of gunfire is obtained. The power of the *K*-8 as an almost impregnable defense against pursuit airplanes is manifest when it is realized that the latter must approach within 200 to 400 yards of a bomber to score effective hits.

Installed in aircraft gun turrets, the *K*-8 gunsight automatically corrects deflection between the line of sight and the gun. It is only necessary that the gunner keep a ring of light in the sight aligned with the target, for the gun to be corrected for all factors affecting the course of the bullet as well as for the target's relative velocity. All this computation is done electrically, and the final voltage representing the desired offset is relayed to an electronic servosystem which corrects for it.

The *K*-8 is an advance over the earlier mechanical gunsights in that it is instantaneous whereas computations attendant upon use of the mechanical ones entailed a time lag. It is complete, correcting as it does for all factors affecting the projectile. Mechanical computers have had to neglect the effect of altitude and indicated air speed, and only two of the remaining factors could be used at one time for a given computation. Finally, the *K*-8 is compact. If any mechanical gunsight were to incorporate corrections for all the factors accounted for by the *K*-8, its mechanism would fill the gun turret.

The *K*-8 has the added recommendation of ease of manufacture. Many of the parts of the electric computer are standard radio equipment, and a large part of the assembly work consists of wiring up the various components. Considerably less skilled labor is employed in its production, resulting in lower first cost and cheaper maintenance.

Operation of the *K*-8 is relatively simple for a gunner. Once he is experienced in operation the power gun turret itself, five hours instruction should develop the competence necessary to operate the *K*-8. The

computing system developed for the gunsight is expected to see more widespread use in peacetime. It is particularly adaptable for problems involving several variables, which are difficult or impossible to handle by mechanical means.

Explosives Sink Telegraph Poles for Signal Corps

An ingenious method has been developed by the United States Signal Corps for sinking telegraph poles in very loose sand where the ordinary method of boring with an earth auger fails, because sand fills the hole the moment the borer is withdrawn.

A camouflet tube, which is a land mine so charged that it burrows into the ground rather than merely blasting a surface crater, is driven to a depth of five feet. In the tube is inserted a primer and two pounds of explosive. Once this explosive is planted underground, the tube is removed, and the loose sand covers the explosive charge and fills in the excavation made by the mine. The telegraph pole is held upright on the ground directly over the charge by four light guy ropes. When the buried charge is fired the pole sinks to a depth of five or six feet and is embedded firmly by the loose sand falling in around it as packing. If the amount of explosive and the number of primers are increased, poles can be sunk to greater depths.

Silicone-Rubber Gaskets Used in Navy Searchlights

Silicone rubber, a new form of silicone developed in the General Electric Research Laboratory, which retains its elastic properties at temperatures as low as 60 degrees below zero or as high as 575 degrees Fahrenheit, is now being used for gaskets for Navy searchlights which are employed to direct the fire of guns at night.

A gasket of silicone rubber, which remains elastic even at the high temperatures encountered near a high-intensity electric-arc light, is applied to the lens of a 24-inch Navy searchlight

The searchlights must be as close as possible to the battery, and this subjects them to severe jarring each time a gun is fired. To prevent breakage, the front glass has to be mounted with a shock absorber, and the high temperature of the electric arc inside requires that it resist heat.

Formerly asbestos was used, since it was heat-resistant, although it lacks resiliency, a necessary property of the shock absorber to prevent breakage of the glass during gun blast. Silicone rubber now combines the desired resiliency with heat resistance.

Silicone-rubber gaskets also are used on the 12-inch signaling searchlights for the Navy and on the turbosuperchargers in *B-29* bombers where they have been found to meet the necessary specifications. Tests show that a silicone-rubber gasket which seals the cover plate of the compressor casing of a supercharger retains its resiliency after 150 hours of continuous operation at 300 degrees Fahrenheit.

Silicone rubber is a polymer the backbone of which consists of a series of units, each made up of a silicon and an oxygen atom linked together. Attached to the atoms of silicon, on the side, are groups of hydrocarbons. At the present time all the silicone rubber being produced in the United States is being used in high-priority war jobs.

POSTWAR • • • • •

Stimulus to Industry and Employment in REA Program

A potential $5,546,283,000 outlet for goods and services could be realized by a five-year rural electrification program for 3,655,000 rural homes, according to detailed estimates accompanying a proposal recently submitted to the United States Department of Agriculture interbureau committee on postwar programs by the Rural Electrification Administration.

The report is based on data from the 1940 census, from reports of REA-financed cooperatives throughout the country, from actual surveys of unelectrified farms in 600 counties, and on the findings and reports of the various state postwar planning committees. Estimates of line construction costs were made on a state basis, using the prewar cost of line per consumer as a factor. Expenditures for wiring, appliances, and plumbing installations were estimated on the basis of prewar experience modified by technological improvements during the war. The latter computations were made on a national basis.

More than 6,344,000 occupied rural dwellings now do not have central-station electric service, according to the REA surveys. Some of these are close to large cities and probably can be served by extensions from urban power systems; others located in areas of sparse population or isolated by physical barriers probably cannot be reached within the five-year period. But over 3,000,000 can be electrified within the limits of the program, the report forecasts, by extensions from existing rural power systems or from new ones built by local interests wherever they are needed.

The report contemplates construction by both public and private financing though it is the conclusion of the REA committee that co-operative enterprise will provide the principal means of carrying out the proposed plan.

The market which will be opened as a direct result of the construction program has been estimated in detail, and the report refers to but does not estimate the volume of such general building renovation and purchases of new nonelectrical home furnishings as have followed rural electrification in the past.

Cost of constructing the new lines for the complete program is put at $1,020,000,000. On a basis of one man-year of labor for each $2,000 spent, this undertaking should supply 510,000 man-years of labor.

The average newly connected farm will spend $145 for wiring and $400 for appliances and equipment, the preliminary report indicates, and in addition 35 per cent of them will install pressure water systems and plumbing costing $225. Other rural establishments—nonfarm residences and the like, making up 25 per cent of the total—will spend $90 each for wiring and $200 each for appliances, and 25 per cent of them will install plumbing averaging $225.

These expenditures should reach a total of $2,026,241,000 and require 1,013,120 man-years of labor. Wiring accounts for $479,723,000 and 239,861 man-years of this estimate, appliances and equipment for $1,279,240,000 and 639,620 man-years, and plumbing for $267,278,000 and 133,639 man-years.

The report also includes an estimate of the amount of new business arising from additional electrical installations by rural consumers already receiving service. It is anticipated that this will be even greater than that from similar installations by newly served consumers, aggregating $2,500,042,000 and providing 1,250,000 man-years of labor. These are divided as follows: The 2,557,000 presently electrified farms will spend an average of $40 for additional wiring and $300 for new electric equipment, and half of them will average $225 each for plumbing. The 6,800,000 nonfarm rural establishments now receiving service will average $25 each for additional wiring and $150 for electric appliances, and ten per cent of them will install plumbing at an average cost of $150.

The estimated totals for these additional expenditures by already electrified rural places are: Wiring, $272,280,000, providing 136,000 man-years of work; appliances and equipment, $1,787,100,000 and 893,000 man-years; and plumbing, $440,662,000 and 220,000 man-years.

The report does not attempt to break down the five-year figures between private financing and public funds. It does, however, cite a possible three-year program of REA loans for construction of distribution lines, rehabilitation of existing facilities, establishment of additional generation and transmission facilities, and financing installations of plumbing and appliances and other equipment using electricity. Loan funds of $579,000,000 would be needed to effect such a program.

This sum represents new investment.

REA officials pointed out that about $113,000,000 of REA loans that have already been approved have not yet been advanced to borrowers, largely because of wartime restrictions on construction; but approved loans can be used for construction almost immediately upon the lifting of restrictions. REA has applications on hand for additional loans totaling almost $110,000,000; any approved applications from this group would, of course, constitute part of the three-year program, if it is authorized.

The report stressed the principle of area coverage as all-important to both its programs. Otherwise, the report states, there will remain many unserved and unservable pockets, because the cost of bringing electricity to these sparsely settled communities separately would be prohibitive.

Bombardiers Practice in Ground Units

In this prefabricated "7*A*-3 Horizontal Bombings and Dead Reckoning Trainer," which can be assembled indoors or out, are a replica (center) of the bombardiers compartment of the Navy's *PB-4T* and the Army's *B-24* heavy bombers; an instructor's compartment, shown at the left; and a floor screen upon which is projected the image of a target site. Training in bombing, dead-reckoning navigation, intercommunication procedure, and evasive action all are given in the new trainer manufactured by the International Business Machines Corporation. When setting up a bombing problem, the instructor reproduces the conditions of actual flight. By means of his instruments he can control altitude, air speed, and direction. Reproduction of even the rarefied atmospheres of high altitudes (to accustom the bombardier to working in heavy clothing) and the noise and vibration of the motors complete the illusion. The instructor can follow the moves made by the student, and conditions can be held stationary at any point for correction of errors or discussion of method. A ring of light on the image registers the accuracy of each bomb release. The trainer not only diminishes the extra expense and time and greater danger of target practice from an airplane but also obviates the period of readjustment formerly existing between ground training and practice flights.

INDUSTRY.....

Status of Television Discussed at FCC Hearing

The television receiver of the future will cover, in a single receiver, carrier frequencies from 540 kilocycles to 300,000 kilocycles and will receive amplitude- and frequency-modulated broadcasts and television programs, according to C. B. Jolliffe (M '34), chief engineer of the RCA Victor division of the Radio Corporation of America, in a statement made before the Federal Communications Commission at a hearing on frequency allocations. If television service is to be located in the frequency bands below 300 megacycles and also above 400 megacycles, it may be possible to build into a single cabinet a receiver or receivers which will accept all services, either black and white or color, and regardless of the standards which may be used in the different frequency bands.

During the war, RCA alone has had more than 1,000 engineers working on the research, development, design, and production of radio equipment for the Armed Forces. They have worked in the field of vacuum tubes, both transmitter and receiver, cathode-ray tubes, low-, high-, very high-, and super high-frequency transmitting and receiving equipment, modulated, continuous wave, and pulsed. This experience will be reflected in peacetime production.

Before the war, television transmitters were available that were capable of operating at frequencies between 40 and 108 megacycles with a power up to a five-kilowatt peak. Although the war has interfered with the production of the necessary higher-power transmitters and tubes, television transmitters that will generate power of 50 kw up to 108 megacycles and five kilowatts up to 300 megacycles are in the process of design. Prewar receivers, capable of producing a picture approximately 15 by 20 inches, will be replaced by a receiver, now in the experimental stage, that will reproduce a picture approximately 18 by 24 inches in size on a translucent screen with adequate brightness to be viewed in a fairly well-lighted room.

In regard to proposals to move television to frequencies above approximately 450 megacycles, Mr. Jolliffe contends that such a step would necessitate the development of a new and untried system involving a great deal of experiment and change in the present equipment before it can be presented to the public. It is estimated that this conversion would take at least five years during which time television could be reaching the American people on the lower frequencies. According to Mr. Jolliffe, the primary purpose of moving to the higher frequencies is to obtain adequate color television, and this feature should be offered as an addition to the present system rather than as a replacement.

In order to give television its fullest scope for expansion, Mr. Jolliffe recommends that the FCC reaffirm its authorization for commercial television on frequencies below 300 megacycles and that it authorize the use of frequencies above approximately 450 megacycles for the experimental development of a new television system.

Anniversary Movie Presented. With the presentation of a full-length motion picture entitled *Heritage for Victory*, the Western Electric Company commemorated its 75th anniversary in November 1944. The picture, which was produced in Hollywood, dramatizes the growth of the organization over a period of three quarters of a century and thus also depicts the history of the telephone and the telegraph. It will be shown to the Western Electric Company's nearly 100,000 employees throughout the country.

CBS Soon to Broadcast Single-Transmitter Television

The first commercial transmitter which will broadcast both sight and sound signals on the same carrier frequency is being manufactured by the Federal Telephone and Radio Corporation for the Columbia Broadcasting Company. The new transmitter will be installed atop the Chrysler Building in New York, N. Y., and will broadcast programs produced in the studios of WCBW in the Grand Central Terminal Building in New York.

The carrier frequency for the composite signal will lie between 450 and 500 megacycles and the video frequency band will be ten megacycles. Combining visual and aural transmission on the same carrier frequency means a lower first cost, less power consumption, less space requirement, and fewer high-power tubes for the broadcaster and a simplified receiver requiring less tubes for the listener. The fine-screen broad-band high-frequency transmission, which will be introduced, marks an improvement over the coarse-screen picture currently broadcast.

A degree of sharpness and detail twice that attained in present pictures is said to be possible. Larger home screens, greater focal depth, and sharper clarity of objects in motion will accompany the new type of transmission. Extension of the television service beyond the station's present range of 11,000,000 people will depend upon public acceptance of the programs and availability of intercity transmission facilities.

HONORS

Highest Engineering Award Goes to John L. Savage

John L. Savage, internationally prominent engineer long associated with the United States Bureau of Reclamation, has been announced as the recipient for 1944 of the John Fritz Medal, oldest and generally conceded to be the highest award of the engineering profession in America. The citation recognizes his "superlative public service in conceiving and administering the engineering of mammoth dams, both in America and beyond the seven seas."

Born in Wisconsin in 1879, Mr. Savage was graduated from the University of Wisconsin with the degree of bachelor of science in civil engineering in 1902. He entered the United States Reclamation Service in 1903 and, except for a period from 1908 to 1916 as consulting engineer with A. J. Wiley, Boise, Idaho, has continued that connection throughout his entire career. Since 1924 he has been chief designing engineer for the Bureau and as such has had charge of the design of all the great dams under its jurisdiction including the Boulder, Grand Coulee, and Shasta Dams. Furthermore he has been adviser on the design of the Tennessee Valley Authority dams and carried out assignments in Puerto Rico, South America, India, and Australia. At present he is engaged in a consulting capacity on important works in India. He holds the honorary degree of doctor of science from the University of Wisconsin and the gold-medal award for distinguished service of the Colorado Engineering Society. He has been invited as honorary lecturer before the Institution of Civil Engineers of Great Britain. In 1941 he was elected to honorary membership in the American Society of Civil Engineers.

The John Fritz Medal is awarded annually by a board composed of four representatives of the American Institute of Electrical Engineers, the American Society of Mechanical Engineers, the American Institute of Mining and Metallurgical Engineers, and the American Society of Civil Engineers, for notable scientific or industrial achievements, regardless of nationality or sex.

Lawrence D. Bell Receives Aeronautics Medal. The Daniel Guggenheim medal for achievement in aeronautics has been awarded to Lawrence D. Bell for "achievement in design and construction of military aircraft and for outstanding contributions to the methods of production." Since forming the Bell Aircraft Corporation, Mr. Bell has specialized in the construction of fighter aircraft among which are the Airacuda, the Airacobra, and Kingcobra models. His company also is a producer of the Boeing *B*-29 Superfortress. Mr. Bell has been general manager of The Glenn L. Martin Company and the Consolidated Aircraft Corporation. Later he organized his own company. Mr. Bell has served as president of the East Coast and National Aircraft War Production Councils. He is a member of the Institute of Aeronautical Sciences and a past president of the Aero Club of Buffalo, N. Y. The award is made by a committee appointed by the American Society of Mechanical Engineers, the Society of Automotive Engineers, and the Institute of Aeronautical Sciences together with past medalists residing in the United States.

OTHER SOCIETIES

Raise AIME Member Dues

An amendment to the bylaws of the American Institute of Mining and Metallurgy providing for an increase in the annual dues of members of that organization from the former $15 to $20 was adopted recently by the AIME board of directors. Concomitant to this increase are the reduction of the dues paid by junior members to $10 and the abandonment of the $20 initiation fee formerly required of junior members wishing to transfer to the status of member, if the junior member has paid dues for ten years, either as student member or junior member, prior to his transfer.

This method of balancing the AIME budget and at the same time lowering the financial membership requirement for young engineers was adopted in preference to curtailment of any present AIME activities or publications or solicitation of outside subsidy. Among the immediate results of the new program expected by AIME president, Chester A. Fulton, are an increased allocation of funds to the papers and publications committee, an addition to the number of publications an individual member may receive annually without extra charge, and an increase in the allocation of funds available to the committee on local section appropriations. None of the additional revenue will be expended for administrative costs or for maintenance or operation of AIME headquarters in New York, N. Y.

ASRE Announces Grants for Refrigeration Research

Four grants of $500 each, sponsored by the American Society of Refrigerating Engineers, have been made to institutions engaged in refrigeration education and research, according to a recent announcement of the society.

The grants, which are made on the basis of recommendations of the ASRE committee on education and research, have been awarded to the Massachusetts Institute of Technology for research on a standard calorimetric procedure for testing of refrigeration compressors and on the pressure drop in Freon evaporators, and to the Oregon State College for projects to determine the values of film coefficient of heat transfer from metal surfaces to boiling ammonia in a flooded evaporator and to develop methods of preserving fish.

Similar grants have also been made to the University of Illinois and to the University of Tennessee.

AWS Receives Award. Presentation of the Ordnance Distinguished Service award, which was authorized on July 20, 1944, was made to the American Welding Society at the opening session of its annual meeting in Cleveland, Ohio. The presentation was made by Colonel S. B. Ritchie, assistant chief of research and development, Office of the Chief of Ordnance, in recognition "of outstanding and meritorious engineering advisory services, in war and peace, for the development and maintenance of ordnance matériel." The award was accepted by David Arnott, president of the society, and vice-president and chief surveyor of the Bureau of Shipping.

ASCE Assigns Field Secretary to Western Area

Henry M. Thackwell, a member of the American Society of Civil Engineers, has been appointed to the society's staff as field secretary, as of August 17, 1944, to represent the society in an area covering the 11 Western States and Texas. His duties formerly were handled by visits of staff members, whose headquarters were in New York City.

Mr. Thackwell's new assignment will enable him to assist the local sections and student chapters and to give guidance to groups of professional engineering employees in need of information on matters pertaining to employment conditions. He is to serve the members in any way in which he can as a staff member: to locate publishable material of professional interest, to contribute toward the activities of the administrative and professional committees, and, in general, to supervise the society's interests in his area.

AIME Elects 1945 Officers

Election of Harvey S. Mudd, president and managing director, the Cyprus Mines Corporation, Los Angeles, Calif., as president of the American Institute of Mining and Metallurgical Engineers was announced recently.

Other officers elected were: vice-presidents, Donald H. McLaughlin, vice-president and general manager, Cerro de Pasco Copper Corporation, New York, N. Y., and Leo F. Reinartz, manager, Middletown (Ohio) division, American Rolling Mill Company; and six directors, C. H. Benedict, metallurgical manager, Calumet and Hecla Consolidated Copper Company, Lake Linden, Mich.; Robert H. Morris, general manager, the Gauley Mountain Coal Company, Ansted, W. Va.; J. C. Nicholls, assistant to the president, the International Nickel Company of Canada, Ltd., Toronto,

Future Meetings of Other Societies

American Institute of Mining and Metallurgical Engineers. Annual meeting, February 18–22, 1945, New York, N. Y.

American Society of Civil Engineers. Annual meeting, January 17–19, 1945, New York, N. Y.

Institute of Radio Engineers. Winter technical meeting, January 24–27, 1945, New York, N. Y.

Institute of the Aeronautical Sciences. 13th annual meeting, April 1945, Detroit, Mich.

Ontario; Clyde E. Weed, vice-president in charge of mining operations, Anaconda Copper Mining Company, New York; Eugene A. White, manager, Tacoma (Wash.) smelter, American Smelting and Refining Company; and William E. Wrather, director, United States Geological Survey, Washington, D. C.

AWS Announces 1945 Officers

A. C. Weigel, vice-president, Combustion Engineering Company, Inc., New York, N. Y., has been elected president of the American Welding Society, according to a recent announcement.

Other elections include: Isaac Harter, vice-president, the Babcock and Wilcox Company, Barberton, Ohio, to the office of first vice-president; W. F. Hess (M '41), assistant professor of metallurgical engineering, Rensselaer Polytechnic Institute, Troy, N. Y., second vice-president; O. B. J. Fraser, director of technical service on mill products, International Nickel Company, New York, treasurer; and M. M. Kelly, Society Headquarters, secretary. Newly elected directors are: Roger W. Clark, welding engineer, General Electric Company, Schenectady, N. Y.; L. W. Delhi, vice-president, Western Pipe and Steel Company, San Francisco, Calif.; J. F. Lincoln (F '39), president, Lincoln Electric Company, Cleveland, Ohio; and H. Malcolm Priest, engineer of the Railroad Research Bureau, United States Steel Corporation Subsidiaries.

JOINT ACTIVITIES

Engineering Foundation Selects Officers for 1945

The Engineering Foundation has re-elected A. L. Queneau, metallurgist, the United States Steel Corporation, as chairman for 1945; Edwin H. Colpitts (F '12), formerly director, the Bell Telephone Laboratories, as director; and John H. R. Arms as secretary. The new vice-chairman is A. B. Kinzel, chief metallurgist, Union Carbide and Carbon Research Laboratories, Inc.

The research procedure committee will be composed of L. W. Chubb (F '21), Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.; E. A. Prentis, Jr., Spencer, White, and Prentis, Inc.; H. E. Wessman, New York University; W. M. Peirce, the New Jersey Zinc Company; W. Trinks, Carnegie Institute of Technology; and W. A. Lewis (M '39), Armour Research Foundation. Mr. Queneau will represent the Engineering Foundation on the executive board of the National Research Council.

UET 1945 Officers Elected

The re-election of F. Malcolm Farmer (F '13), vice-president and consulting engineer, the Electrical Testing Laboratories, New York, N. Y., as president of United Engineering Trustees, Inc., has been announced by that society.

Other officers elected include vice-presidents Arthur S. Tuttle, consulting engineer, and Everett S. Lee (F '30), engineer in charge, general engineering laboratory, General Electric Company; George L. Knight (F '17), chairman of the finance committee; A. L. Queneau, chairman of the real estate committee; Albert Roberts, treasurer; C. R. Jones (M '30), assistant treasurer. John H. R. Arms, general manager of the corporation, continues as secretary.

EDUCATION . . .

Applications Available for Jewett Fellowships

Applications for the Frank B. Jewett Fellowships for post-doctorate research in the fundamental physical sciences may now be obtained from the Frank B. Jewett fellowship committee, Bell Telephone Laboratories, 463 West Street, New York 14, N. Y.

The applications should be returned to the committee before January 1, 1945, and announcements of awards will be made on March 1, 1945. Applicants who, because of location, will be unable to obtain and return an application before the closing date may apply by a letter which should contain a brief biographical statement, information as to education and previous professional work, a report of research completed or in process, a discussion of the research which the applicant proposes to pursue if appointed, and the name of the institution where he wishes to work. Three or four names should be furnished for references regarding the applicant's scientific qualifications and potentialities.

Westinghouse Company Forms New Educational Department

Formation of a new educational department, co-ordinating all of the company's relations with schools, colleges, and universities, has been announced by the Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa.

The new department will consist of three main divisions: school service, which provides teaching aids and science information to schools and other educational institutions, and is directed by Charles W. McLean; university relations, which administers the company's scholarships and fellowships and supervises the recruiting of graduate student employees under the management of Howard C. Madsen (A '42); and the student training division, with O. D. Montgomery as manager, which supervises the training of all graduate students for the company.

IRE Elects Officers for 1945

Election of William L. Everitt (F '36), chief of the operational research branch, Office of the Chief Signal Officer of the United States Army, Washington, D. C., as president of the Institute of Radio Engineers, has been announced by the board of directors of that society.

Also elected were Hendrik J. Van der Bijl (M '17), chairman of the Electricity Supply Commission, Johannesburg, Transvaal, Union of South Africa, as vice-president of the institute; and for three-year terms as directors; Stuart L. Bailey, consulting radio engineer, Jansky and Bailey, Washington, D. C.; Keith Henney, editor of *Electronics*, New York, N. Y.; and Benjamin E. Shackelford (M '42) engineer-in-charge, frequency bureau, Radio Corporation of America, New York.

LETTERS TO THE EDITOR

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers. Publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Postwar Curriculums in Electrical Engineering

To the Editor:

The article "Postwar Curriculums in Electrical Engineering" by R. G. Kloeffler in the October issue of *Electrical Engineering* interested me very much as I had some thoughts along the same line.

I think Mr. Kloeffler has brought to the fore a most important factor, which properly can influence the future of our country, not just in electrical engineering but in all fields of engineering. Mr. Kloeffler advocates the introduction of nontechnical courses into the engineering curriculum, so that the engineer will be better adapted to do his bit toward bettering the world economically,

Table I

Freshman			
English I	3	English II	3
Mathematics I	3	Mathematics II	3
Physics I	3	Physics II	3
Physics Laboratory I	1	Physics Laboratory II	1
Chemistry I	3	Chemistry II	3
Chemistry Laboratory I	1	Chemistry Laboratory II	1
Engineering drawing I	2	Engineering drawing II	2
Military science and tactics—Basic I	2	Military science and tactics—Basic II	2
Basic Electrical engineering I	1	Basic Electrical engineering II	1
Total	19	Total	19
One month summer session . . . Surveying			4 hours
Sophomore			
American History	3	Public speaking	3
Mathematics III	3	Technical reports	1
Physics III	3	Principles of electrons	2
Physics Laboratory III	1	Mathematics IV	3
Electrical engineering I	3	Physics IV	3
Metallurgy	2	Physics Laboratory IV	1
Metallurgy Laboratory	1	Electrical engineering II	3
Geology	1	Electrical engineering Laboratory II	1
Military science and tactics—Basic III	2	Military science and tactics—Basic IV	2
Total	19	Total	19
One month summer session . . . . Welding, foundry, machine tools, precision tools, and shop practice			4 hours
Junior			
Economics	3	Accounting	3
20th century history	3	Electronics	4
Thermodynamics I	3	Electronics Laboratory	1
Thermodynamics Laboratory I	1	Electrical engineering IV	3
Electrical engineering III	3	Electrical engineering IV Laboratory	1
Electrical engineering III Laboratory	1	Thermodynamics II	3
Precise Electrical Instruments Measurement Laboratory	2	Thermodynamics II Laboratory	1
Advanced military science and tactics or elective	3	Advanced military science and tactics or elective	3
Total	19	Total	19
Six weeks military summer camp or summer industrial employment with written paper			4 hours
Senior			
Political science	3	Music and literature	2
Hydraulics	2	Strength of materials	2
Hydraulics Laboratory	1	Strength of materials Laboratory	1
Electrical engineering V	3	Electrical engineering VII	3
Electrical engineering VI	3	Electrical engineering VIII	3
Electrical engineering V Laboratory	1	Electrical engineering VII Laboratory	1
Industrial planning	2	Industrial management	2
Engineering applications to biological science	1	Industrial economics or Industrial applications	1
Advanced military science and tactics or elective	3	Advanced military science and tactics or elective	3
Total	19	Total	19

politically, and socially as well as in the field of engineering. I am in full accord with his ideas but also wish to expand them with some of my own.

A person who has gone to an engineering institution usually is educated principally in the field of physical science with some broadening of thoughts in the field of social science. This person may be invaluable in his own field but can offer nothing to society as a whole. How much better equipped this person would be to add something to the world, as well as himself, if he had been educated in humanistics, biological science, the use of his hands, and the general over-all picture of how these fields effect each other.

Along this line let us therefore make provisions for some more nontechnical courses in addition to those suggested by Mr. Kloeffler, such as those listed below:

Industrial planning	3 hours
Industrial management	2 hours
Accounting	3 hours
Industrial economics, or Industrial application of electrical equipment	1 hour
Engineering applications to biological science	1 hour
Geology	1 hour
Metallurgy	3 hours
Military science and tactics—basic (compulsory)	8 hours
Advanced military science and tactics (optional)	12 hours
One month summer session of practical instruction in welding, foundry, use of machining tools, and precision mechanical work	4 hours

This would give us the broad tentative schedule shown in Table I.

The foregoing would be a total of 163 credit hours and this would be quite a heavy schedule for a student. At the same time there are not quite enough electrical-engineering courses (40 credit hours) to give the student all the specific electrical knowledge he might desire, but, on the other hand, the graduate would have a well-rounded education that would fit him better for the over-all aspects of the business and social world.

The reason for including military science and tactics is to give the student an opportunity to be prepared to help his country in a crisis such as we had December 7, 1941. The present success of the war is due largely to the many available reserve officers who were called to active duty. What the Ordnance Department has done is a fine example of how many reserve officers who had experience in research, engineering, and production work helped to take over almost similar functions in the military service to help make the United States the "arsenal of the world."

My own work as a maintenance specialist of antiaircraft artillery and fire-control equipment has been very broadening, but I was handicapped by the lack of previous instruction in the use of precision machine tools and welding.

The Army has been excellent experience to many of us lucky enough to be in a technical service, for we have had experiences in being the military supervisors of sections which are civilian in man power and in many ways of operation. It has been necessary to do maintenance in the field and to give advice and instruction to the men using the equipment, as well as to analyze and write maintenance procedures.

My contention is: let the college furnish the broad and well-rounded education, and either let the industrial concerns educate their engineer employees in the more specific electrical knowledge for their job or jobs or add a fifth semester of specialized study to the curriculums.

A man who is better able to see and meet the social and economic problems of today and who has an understanding of human nature will be a better man in his community and in his job. And, because he can do mechanical work with his hands, his opportunities in the field of hobbies are broader, and a man who has no spare time on his hands for loafing is a better and happier man.

H. L. ABBOTT (A '44)

(First lieutenant, Ordnance Department, United States Army, Philadelphia, Pa.)

NEW BOOKS • • •

The following new books are among those recently received from the publishers. Books designated ESL are available at the Engineering Societies Library; these and thousands of other technical books may be borrowed from the library by mail by AIEE members. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books. All inquiries relating to the purchase of any book reviewed in these columns should be addressed to the publisher of the book in question.

Reports on Progress in Physics, volume 9, 1942–43. Edited by W. B. Mann. Published by The Physical Society, 1 Lowther Gardens, Exhibition Road, London, S.W.7, England; printed by Taylor and Francis, Ltd., Red Lion Court, Fleet Street, London, E.C.4, 1943. 353 pages, illustrated, 10 by 7 inches, cloth, $6. (ESL.)

The new volume of this valuable series covers two years, instead of one, because of the need for economy. It includes ten reports on advances in our knowledge of atmospheric physics and chemistry and reports on other important fields, such as solar physics, the structure of rubber, counter tubes, field emission of electrons, physics and the search for oil, sound, crystal dynamics and X-ray scattering, and the physics of paintings. As usual, the articles have useful bibliographies.

Thorpe's Dictionary of Applied Chemistry, volume VI. By J. F. Thorpe and M. A. Whiteley. Fourth edition revised and enlarged with an index to volumes I–VI by J. N. Goldsmith. Longmans, Green and Company, London, England; New York, N. Y.; Toronto, Ont., 1943. 611 pages, illustrated, 9½ by 6 inches, cloth, $30. (ESL.)

Volume VI of the new edition of this

well-known reference work follows the pattern of the earlier ones. In addition to a wide variety of topics treated succinctly in dictionary style, it includes comprehensive articles on glazes and frits, beryllium, glue, glycerin, gold, hafnium, hydrogenation, helium, homogeneous catalysis, hydrogen, and gum inhibitors.

Twentieth Century Engineering. By C. H. S. Tupholme. Philosophical Library, New York, N. Y., 1944. 201 pages, illustrated, 9 by 5½ inches, cloth, $3. (ESL.)

Intended to give the layman an account of "some of the more spectacular engineering progress during recent years," this work deals with developments in mechanical power, workshop processes, air conditioning, refrigeration, chemical and metallurgical engineering, electrical engineering, traction, marine engineering, aircraft, and physics. The book is an American reprint of one published in England in 1942.

Essentials of Precision Inspection. By W. Mollard. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1944. 207 pages, illustrated, 11 by 8½ inches, cloth, $3. (ESL.)

This manual offers a systematic course of instruction in the use of the instruments employed in interchangeable manufacturing. These instruments are described; methods of checking their accuracy given; and their uses for various purposes explained and illustrated by problems.

Theoretical Chemistry. By S. Glasstone. D. Van Nostrand Company, New York, N. Y., 1944. 515 pages, illustrated, 9½ by 6 inches, leather, $5. (ESL.)

As the subtitle indicates, this book is concerned with those aspects of quantum mechanics, statistical mechanics, and molecular spectra that have a bearing on chemical problems. It is intended to provide an introduction that will enable the reader to understand clearly how quantum mechanics and statistical mechanics have been used in chemical work, and also to provide a foundation for further study.

Plastic Molds. By G. B. Thayer. Second edition. American Industrial Publishers, Cleveland 6, Ohio, 1944. 136 pages, illustrated, 9¼ by 6 inches, cloth, $3.50. (ESL.)

An experienced engineer here presents his ideas on the design and construction of molds. The various classes of molds used in compression and injection molding are described, and detailed description of various molds given. New material has been added to this edition, including contributions by several collaborators.

Bibliography and Abstracts on Electrical Contacts. Prepared by committee *B*-4 on electrical-heating, electrical-resistance, and electric-furnace alloys. American Society for Testing Materials, 26 South Broad Street, Philadelphia, 1944. 137 pages, tables, 9½ by 6 inches, cloth, $5. (ESL.)

This bibliography lists and, for most entries, abstracts over 800 publications on electric contacts. The arrangement is chronological, but subject and author indexes are provided. Among the subjects included are electric contacts in general, contact materials, circuit-breaker design, contact resistance and temperature, the electric arc, spark and glow discharges, contact wear, and circuit parameters as applied to contact operations.

ASTM Standards on Electrical Insulating Materials. Prepared by ASTM committee *D*-9 on electrical insulating materials; specifications, methods of testing, February 1944. American Society for Testing Materials, 260 South Broad Street, Philadelphia 2, Pa., 1944. 502 pages, illustrated, 9 by 6 inches, paper, $2.75. (ESL.)

This pamphlet contains the latest report of the committee on insulating materials, which proposes a routine method for testing the gas content of insulating oil and methods of testing askarels, and discusses the significance of tests of electrical insulating materials. It also contains the methods developed by the Society for testing varnishes and lacquers, molded insulating materials, plates, tubes, mineral oils, ceramic products, rubber, mica, and other insulating materials.

Nobel—Prize Donor. By M. Evlanoff. Published by the Blakiston Company, Philadelphia, Pa.; distributed by Fleming H. Revell Company, New York 10, N. Y.; London, England; and Edinburgh, Scotland, 1943. 190 pages, illustrated, 8¼ by 5¼ inches, cloth, $2.50. (ESL.)

This is the history of the Nobels, father and sons. The major part of the book is devoted to Alfred Nobel, the inventor of dynamite and creator of the Nobel prize. Attention also is given to the less known work of his brothers, Robert and Ludwig, and the immense oil industry which they founded in the Caucasus.

Pipeline to Battle. By P. W. Rainier. Random House, Inc., New York, N. Y., 1943. 302 pages, maps, 8½ by 5½ inches, cloth, $2.50. (ESL.)

The author of this interesting account of the African campaign of the British Eighth Army is an experienced mining engineer who joined the Royal Engineers in 1940 and served through the African campaign. His major task was to get water to the men in the front lines, and he laid pipe lines, drilled wells, and built waterworks throughout the campaign. His account of desert warfare is a vivid readable one, mostly written in the field.

System of Mineralogy. James Dwight Dana and Edward Salisbury Dana, Yale University 1837–1892, seventh edition, entirely rewritten and greatly enlarged. By C. Palache, H. Berman, and C. Frondel. Volume I, Elements, Sulfides, Sulfosalts, Oxides. John Wiley and Sons, Inc., New York, N. Y.; Chapman and Hall, London, England, 1944. 834 pages, illustrated, 9¼ by 6 inches, cloth, $10. (ESL.)

The new edition of this classic reference book will be welcomed by all students of mineralogy. As now issued, it is essentially a new book. Among the improvements are a new system of classification, a revision of morphological elements, a new way of presenting crystallographic data, introduction of optical characters, and other changes occasioned by the advances in the science during the last 50 years.

Control of Germany and Japan. By H. G. Moulton and L. Marlio. Brookings Institution, Washington, D. C., 1944. 116 pages, tables, maps, 9¼ by 6 inches, cloth, $2. (ESL.)

This new publication of the Brookings Institution is concerned with the problem of preventing future military aggression by Germany and Japan. The possibilities of their control by various economic measures, such as restriction of the importation of raw materials and the control of key industries are discussed, and the disadvantages of various plans are noted. A military control plan is described, which offers possibilities of success and which the authors believe to be the only effective means of checking aggression.

PAMPHLETS . . . .

The following recently issued pamphlets may be of interest to readers of "Electrical Engineering." All inquiries should be addressed to the issuers.

Organo-Silicon Films. By Francis J. Norton. General Electric Company, Schenectady, N. Y., 11 pages.

Second New England Traffic Engineering Conference. National Conservation Bureau, 60 John Street, New York 7, N. Y., 74 pages.

Simplified Spanish. Pan American Society, Box 315, Quito, Ecuador, South America, no charge.

Glossary of Foreign Welding Terms. American Welding Society, 33 West 39th Street, New York 18, N. Y., 16 pages, 50 cents.

Standards for the Installation and Operation of Centrifugal Fire Pumps. National Board of Fire Underwriters, 85 John Street, New York 7, N. Y., 52 pages.

The Financial Record of the Electric Utility Industry, 1937–43. Federal Power Commission, Washington, D. C., 10 pages, no charge.

Federal Agencies. Citizens National Committee, Inc., 1409 L Street, NW, Washington 5, D. C., 68 pages, 25 cents.

Postwar Planning in the United States. Twentieth Century Fund, 330 West 42nd Street, New York 18, N. Y., 151 pages, $1.

Good Public Relations for the General Contractor. Associated General Contractors of America, Inc., 10 Rockefeller Plaza, New York 20, N. Y., 24 pages.

Facilities Expansion. Bureau of Census, Washington 25, D. C.

Multiple Industrial Tenancy. Smaller War Plants Corporation, Washington, D. C., 18 pages.

Republic Goes to War. Republic Steel Corporation, Cleveland 1, Ohio, 94 pages.

V-Belt Handbook for Industrial Applications. The B. F. Goodrich Company, Akron, Ohio, 74 pages.

Business Engineering in the Shipyards, 8 pages. **Production Weapons,** 8 pages. George S. May Business Foundation, 11 South Dearborn Street, Chicago, Ill.

TRANSACTIONS SECTION

Preprint of Corresponding Pages From the Current Annual AIEE Transactions Volume

The Scientific Basis for the New British System of Cockpit Lighting

EDWARD S. CALVERT
NONMEMBER AIEE

Synopsis: The new British system uses ultraviolet for the illumination of the instrument markings and red floodlighting for the general illumination of the cockpit. The scientific basis for this system, which is known as the dual system of cockpit lighting, is discussed, and some details of the fittings are given. Particular emphasis is laid on the layout of the cockpit, correct layout being regarded as the most important single factor for the success of the whole system.

In order to operate an aircraft at night, and particularly a military aircraft, with the maximum comfort, safety, and efficiency, the pilot must be able to read his instruments at a glance, but the method used to render the instrument markings legible must not be such as to reduce appreciably his ability to see objects outside the aircraft. Anyone who has tried to look out of a lighted room at night knows that the brightness level inside the room must be low if anything much is to be seen outside. This was realized from the beginning of cockpit lighting, and the markings on the instruments until recently have been self-luminous and could be read, although with some difficulty, without any lighting at all. However, as controls, switches, radio equipment, messages, maps, and so forth also must be observed or read at times, it has in the past been the custom to install a system of general lighting, usually white, for use when required, these lights being controlled by means of dimmers.

Had the right color been chosen for the self-luminous paint and for the lighting, and had cockpits been laid out so as to make it possible to put the lights in reasonable positions for good illumination, then, operationally this system would have been satisfactory. It is, however, the fact that the wrong color, that is, green, was chosen for the self-luminous paint, and that the right color, that is, red, was not always chosen for the lighting. Also, until night fighting forced attention to the problem the lighting was not considered to be important enough to be taken into account in the initial layout of the cockpit, with the result that some types of aircraft were built with cockpits which, without extensive structural alterations, could not be illuminated adequately by any method whatsoever.

It is the object of this paper to show from the properties of the dark-adapted eye what the colors of the markings and of the cockpit illuminant should be, and also to indicate the few simple precautions which have to be taken in the layout of the cockpit and the positioning of the lamps to insure good results. The layout of the cockpit is considered to be by far the most important single factor in cockpit lighting, but for convenience the color of the markings will be considered first.

Color of Markings

It is common knowledge that the ordinary green self-luminous markings cannot be focussed sharply by the normal dark-adapted eye at the distances at which these markings are observed, that is, about 18 inches or more. If the color is changed to orange without altering the brightness of either the markings or their background, it will be found that the markings stand out with a distinctness most surprising to those who for years have put up with the ordinary "fuzzy" green markings. Unfortunately orange self-luminous compounds of sufficient brightness have not been available until quite recently, and little is known as yet of their durability in service. Red self-luminous compounds of sufficient brightness are not available at the present time, and there are reasons for believing that they never will be.

Important as distinctness of markings undoubtedly is, there is still a stronger reason for changing from green to red or orange. In the dark-adapted eye the ratio of parafoveal to foveal sensitivity decreases from about 500 in the blue and 200 in the green, to about 10 in the yellow–orange and 0.8 in the red. When the pilot is looking out of the cockpit, the images of the markings are thrown on the parafovea, that is, are seen in the tail of the eye, and it is this parafoveal sensitivity ratio which determines the distracting effect of the cockpit lighting. In other words, what is wanted are markings of such a color that they appear to come up bright when the observer looks directly at them, but fade out as soon as the observer looks away from them. Deep red meets this requirement very closely, but even orange–red is a very great improvement on blue–green.

The reduction in the distracting effect of the markings is the fundamental reason for changing the color from green to orange, and for selecting red as the color of the general lighting, but there are other important reasons:

(*a*). As the specular reflectivity of the sidescreens is of the order of ten per cent, it follows that reflections of objects inside the cockpit cannot be seen in the sidescreens either foveally or parafoveally if the general illumination of the cockpit is such that the brightness of these objects is less than about ten times threshold. If white were used, these reflections seen parafoveally would appear to have a brightness about the same as the actual objects seen foveally.

(*b*). Because of the relative insensitivity of the parafovea to red, there is little or no danger of scattered light from the cockpit giving away the position of the aircraft to an enemy.

(*c*). The time taken for the eye to pass from the light to the dark-adapted state is very considerably shortened if adaptation takes place in the presence of weak red light instead of in complete darkness. If dark adaptation is lost due to the aircraft being caught in searchlights or through the use of a hand torch in the cockpit, then recovery of dark adaptation is hastened.

(*d*). Recent research indicates that in the presence of weak red light the final state of dark adaptation is not impaired to an appreciable degree, and, indeed, may be slightly better than in complete darkness.

As the last of the afore-mentioned reasons may be questioned, it is worthy of note that a similar result was obtained quite independently in tests using a typical single-seat cockpit fitted with instruments having yellow painted markings and illuminated with weak red light. It was found that after observing these markings, representative targets outside the cockpit could be picked up in times which were about ten per cent shorter

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than were obtained in complete darkness. This result seems to be explainable only on the assumption that the eyes are slightly more sensitive in weak red light.

Layout of Cockpit

All modern operational aircraft have totally enclosed cockpits. The enclosing surfaces must be polished in order to be transparent, and there is no practicable method of preventing these polished surfaces from reflecting whatever objects happen to bear the correct geometrical relationship with the observer's eye. It follows that reflections can be eliminated only by adopting the principle of the reflectionless shop window, that is, by arranging that the important surfaces, namely, the windscreen and those parts of the sidescreens immediately adjacent to it, shall reflect some surface of low brightness, that is, which is painted mat black. This black surface obviously must take the form of a coaming underneath the windscreen, as shown in Figure 1. In new designs such a coaming can be incorporated without detriment to the general layout, and even in existing types of British aircraft no case yet has been found in which a substantial coaming could not be fitted.

As regards the positioning of the lamps, the chief trouble is to avoid reflections of the light source itself in the cover glasses of the instruments on the panel. It follows from the geometry of the layout shown in Figure 1 that the pilot will not see images of the light source if the lamps are mounted as high or higher than the top of the upper row of instruments, and that the correct place to mount the lamps is underneath the coaming. The coaming therefore serves to prevent reflections both in the windscreen and in the cover glasses of the instruments. Where ultraviolet radiation is used the coaming has a further purpose.

It is obvious that the whole inside of the cockpit should be mat black and that the pilot's clothing, and particularly his gloves, also should be black. Instruments should not have protruding bezels or knobs which would cut off the light from other instruments. Markings should be bold, all of one standard size, and should be shaped and proportioned to give maximum legibility. Instruments with markings smaller than standard, if possible, should be grouped nearer the lamps than those with the larger markings. The instruments at the sides and bottom of the panel should be tilted so that neither the pilot's view of them nor the illumination incident on them is unduly oblique.

Methods of Cockpit Lighting

If it is assumed that the cockpit will be laid out and the lamps mounted as described previously, then the simplest solution would be to have the markings in orange self-luminous paint and to use red general cockpit lighting capable of being dimmed to extinction. It easily can be shown that markings which are just bright enough to be seen in complete darkness are bright enough to be seen on moonlit nights and in twilight. In any case, the general lighting system, if properly installed, can be used to boost the brightness of the markings if abnormal conditions arise, as for instance, when the aircraft is caught in searchlights. This paint is already used in a few British instruments, notably the lubber lines on the magnetic compass.

However, even if a satisfactory orange self-luminous paint should be forthcoming, there are objections to it on production and maintenance grounds, and therefore it was decided not to use it in the new British system of cockpit lighting. Red light on plain white painted markings was tried, but it was found that the markings appeared flat, owing partly to the deep-red color and partly to the fact that the contrast between the markings and their background in practice seldom

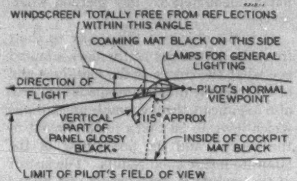
WINDSCREEN TOTALLY FREE FROM REFLECTIONS WITHIN THIS ANGLE
COAMING MAT BLACK ON THIS SIDE
LAMPS FOR GENERAL LIGHTING
DIRECTION OF FLIGHT
PILOT'S NORMAL VIEWPOINT
VERTICAL PART OF PANEL GLOSSY BLACK
115° APPROX
INSIDE OF COCKPIT MAT BLACK
LIMIT OF PILOT'S FIELD OF VIEW

Figure 1. Antireflection coaming

Reflected rays and image of coaming in windscreen shown dotted

exceeds 20 to 1. Also, most existing cockpits contain small miscellaneous objects which are light colored or give small specular reflections. For these reasons it was decided to use orange fluorescent markings and to supplement the red lighting with ultraviolet radiation, thereby obtaining the desired distinctness. This combination also permits both red and ultraviolet to be used at low intensities, thereby reducing troubles from specular reflections due to the red, or from eyeball fluorescence due to the ultraviolet. Also, either system acts as a standby for the other in case of lamp failures. This whole system is known as the dual system and has been adopted as the standard method of cockpit lighting for all operational types of British aircraft.

Another method of rendering the instrument markings legible is to build lamps into each instrument, or light them from behind the panel as in automobiles. Unfortunately aircraft instruments, being of all shapes, sizes, and types, do not lend themselves well to being lighted in this way, and great difficulty is experienced in securing uniform dimming and uniform dial brightness, and in preventing light from leaking out round the edges of the bezels. These leakages can be overcome by the use of ultraviolet in some form, but the great disadvantages of the method as regards production and maintenance still remain, these disadvantages being even more marked in the case of British aircraft which have not hitherto had earth return. In any case, this method has to be used in conjunction with a floodlighting system in order to illuminate the large amount of gear which, in modern aircraft, lines the sides of the cockpit.

Fittings

The chief requirement for the fittings is to keep the size down. The red lamps used in the dual system are 2.4 inches long by 0.75 inch in diameter and accommodate a lamp of three watts. Two of these under the coaming usually can be arranged to flood the whole cockpit, that is, the instrument panel and the two sides. A local light is always required over the magnetic compass, but, since the needle, grid wires, and lubber line are orange self-luminous, this light is only used when setting a new course.

Ultraviolet radiation, if allowed to enter the eye, produces the effect of a blue mist, but in the dual system this is prevented partly by the coaming and partly by screening the lamps. As only a small amount of ultraviolet can be used without detriment to vision, the radiation should be obtained from tungsten filament lamps so as to obviate the difficulties associated with gaseous-discharge tubes, that is, dimming and radio interference. In the dual system two seven-watt fittings have been found sufficient for single-seat cockpits and four for two-seat cockpits.

Since, in the dual system all lights would go out if the aircraft electric supply failed, one additional orange lamp is fitted over the flying instrument panel, and is supplied from a separate alkaline accumulator. The members of the air crew also are issued with hand torches which may be fitted with red bulbs.

Concluding Remarks

The dual system now has been fitted to many types of aircraft and tested by many pilots, and in no case has any report adverse in principle been made.

So many conflicting requirements have to be met in the layout of a cockpit that an entirely happy solution to the lighting problem is not always possible, but there is no doubt that the aforementioned principles, if borne in mind in the early stages of the design and applied with ordinary ingenuity, will lead to reasonably satisfactory installations.

Considerations in Servomechanism Design

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Synopsis: A servomechanism is in general any closed-cycle regulated system that is controlled by a difference of quantities. In this paper, methods are outlined by means of which the steady-state and transient performance of servomechanisms can be calculated. A general solution in operational form is given, and specific solutions are derived for a number of different types of angular-position servomechanisms. Among these is the solution for the Ward-Leonard type of control with RC antihunt feedback. This is probably the most common type of angular-position control.

SERVOMECHANISMS include many familiar regulator systems. The simple float valve controlling water level in a tank and the voltage regulator in reality are servomechanisms. The war has brought about many important new applications including: holding airplanes and ships on predetermined courses; stabilizing and rotating guns; producing exact duplicates of intricate patterns and dies; indicating flap or landing-gear position; and a multitude of others. Probably the most common servomechanism system is that which matches the position of a high-torque shaft to that of a low-torque shaft. This will be referred to as an angular-position servomechanism. By means of this servomechanism the high power required to operate a gun turret can be controlled so that the gun accurately matches the position of a low-power hand-operated sight. Whether the operating power is electric, hydraulic, or a combination of these or other types of power, the analysis to follow provides a basis for obtaining servomechanism performance in terms of basic design parameters.

Definition of a Servomechanism

In Figure 1, the nature of the component parts involved in a servomechanism and the meaning of the term closed-cycle are clearly illustrated. The three fundamental parts are the error measurer, the controller, and the output-quantity control member. As shown by the interconnecting arrows each of these basic parts is dependent for its operation upon one of the others and in turn influences the operation of the remaining part, hence the use of the term closed-cycle as shown by the closed counterclockwise system.

As previously defined, a servomechanism is in general any closed-cycle regulated system that is controlled by a difference of quantities. The wide scope of this definition can be realized best when it is noted that no limitation is placed on either the input or output quantities. Thus we may have regulation of speed, voltage, position, flow, and so forth. If the error measurer contains an element for converting quantities, the input and output quantities need not be the same. Many servomechanism problems have been solved commercially by Rototrol[11] or Amplidyne control or regulating systems. The basic component of each of these systems is rotating d-c equipment to which suitable control, either of the electronic or some other type, has been added.

The General Servomechanism

Figure 1 illustrates the basic elements of a general servomechanism and their interrelation. A theoretically perfect servomechanism would be one in which the output quantity varied with time exactly as the input. Referring to Figure 1 it is seen that this is not possible, since no error would be developed by which the output member could be controlled. The design of servomechanisms deals with methods of keeping both the magnitude and transient duration of the error between input and output small enough to meet the desired operating conditions.

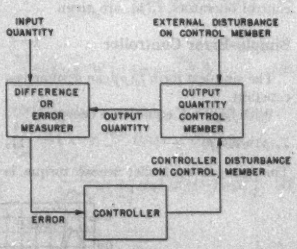

Figure 1. General servomechanism block diagram

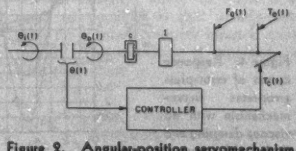

Figure 2. Angular-position servomechanism

The various elements in Figure 1, may be represented mathematically as time functions as follows:

$i(t)$ = input measurement as a function of time
$O(t)$ = output measurement as a function of time
$E(t)$ = error measurement as a function of time
$C(t)$ = control of output member as a function of time
$C_o(t)$ = external disturbance of output control member as a function of time

Also:

$$E(t) = i(t) - O(t) \tag{1}$$

The Laplacian operator form of any time function is given by

$$\phi(p) = p \int_0^\infty e^{-pt} \phi(t)\,dt \tag{2}$$

If $\phi(t)$, $\phi'(t)$, $\phi''(t)$, and so on $= 0$ at $t = o$, p may be thought of as equivalent to $\frac{d}{dt}$. When equation 2 is used, equation 1 becomes

$$E(p) = i(p) - O(p) \tag{3}$$

Also:

$$C(p) = f_c(p) E(p) \tag{4}$$

$$O(p) = f_o(p)\,[C(p) + C_o(p)] \tag{5}$$

where

$f_c(p)$ is the response function of the controller.
$f_o(p)$ is the response function of the output control member.

Both of the above quantities are similar to the response function of an electric network. In the familiar response of an LR series circuit, $\frac{1}{R+LP}$ corresponds to $f_c(p)$ of equation 4, and $C(p)$ and $E(p)$ are analogous to the current and impressed voltage, respectively.

By substituting equations 3 and 4 into equation 5 and solving for $E(p)$, one obtains

$$E(p) = \frac{i(p) - f_o(p)\,C_o(p)}{1 + f_o(p) f_c(p)} \tag{6}$$

This is the basic servomechanism equation and is of the type attributed to an unpublished memorandum of J. Taplin in 1937.[1] Taplin recognized the similarity of the automatic-control problem and the amplifier-design problem as given by Black[2] and Nyquist.[3] Integrating $E(p)$ in the Bromwich Wagner integral yields $E(t)$.

Over a period of years a number of solutions of equation 6 have been made. Certain assumptions and approximations

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Some of the material for this paper has been abstracted from a thesis submitted to the University of Pittsburgh in partial fulfillment of the requirements for the degree of doctor of philosophy.

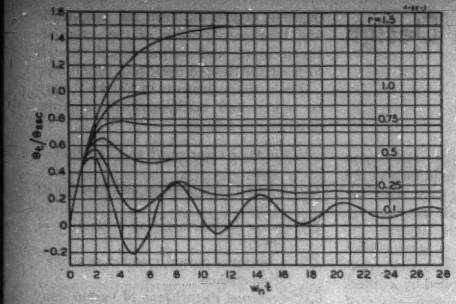

Figure 3. Response curves of simple-error servomechanism

were used to obtain these solutions. If these same assumptions and approximations can be justified by the designer, the established equations may be used, and the need for obtaining a new solution of equation 6 will have been eliminated. Once the characteristic equations of any given type of servomechanism have been obtained, they may be applied to any servomechanism of that type regardless of what the controlled parameter is. These equations permit analysis from which it is possible to design equipment to meet certain specifications. Stability as well as transient and steady-state errors can be predicted.

A good method to follow in the design of a servomechanism is to separate the mechanism into its component parts as shown by Figure 1, then to calculate the response functions of these components, and finally either to use an established solution of equation 6 such as those following or to obtain a new solution.

Angular-Position Servomechanism

The procedure to be followed in making an analysis of a servomechanism can be illustrated by consideration of the relatively common angular-position servomechanism. Such a system is schematically illustrated in Figure 2.
Where

$\theta_i(t)$ = input angle as a function of time
$\theta_o(t)$ = output angle as a function of time
$\theta(t) = \theta_i(t) - \theta_o(t)$ = error angle as a function of time
c = viscous damping coefficient of output member
I = lumped inertia of output member
$F_o(t)$ = coulomb friction as a function of time
$T_o(t)$ = external load torque as a function of time
$T_c(t)$ = controller torque as a function of time
$w_i(t)$ = input velocity as a function of time

The response of the output member can best be obtained by writing its differential equation:

$$I\frac{d^2\theta_o}{dt} + c\frac{d\theta_o}{dt} + T_o(t) + F_o(t) = T_c(t) \qquad (7)$$

At $t=0$ with $\frac{d\theta_o}{dt}$ and $\theta=\theta_o$ the Laplacian form of the foregoing solved for $\theta_o(p)$ is

$$\theta_o(p) = \frac{1}{Ip^2+cp}\,(T_c(p) - T_o(p) - F_o(p)) \qquad (8)$$

Comparing equation 8 and equation 5 one finds

$$f_c(p) = \frac{1}{Ip^2+cp}$$
$$C(p) = T_c(p)$$
$$C_p(p) = -T_o(p) - F_o(p)$$

By substituting into equation 6, one obtains

$$\theta(p) = \frac{(Ip^2+cp)\theta_i(p) + T_o(p) + F_o(p)}{Ip^2+cp+f_c(p)} \qquad (9)$$

Since $p\theta_i(p) = w_i(p)$, equation 9 can be written as

$$\theta(p) = \frac{(Ip+c)w_i(p) + T_o(p) + F_o(p)}{Ip^2+cp+f_c(p)} \qquad (10)$$

Thus once a control operator, $f_c(p)$, is determined, we have an error equation for either an angular-displacement or an angular-velocity input disturbance. Several solutions of equation 10 with different control operators, $f_c(p)$, are given.

Simple-Error Controller

The simplest form $f_c(p)$ can assume is a constant.

With $f_c(p) = K$ equation 4 becomes

$$T_c(p) = K\theta(p) \qquad (11)$$

This gives a controller whose torque is proportional to the error angle, and K is known as the stiffness constant. If $f_c(p) = K$, $T_o(p) = F_o(p) = 0$, and $w_i(p)$ is made w_i at $t=0$, equation 10 becomes

$$\theta(p) = \frac{(Ip+c)w}{Ip^2+cp+K} \qquad (12)$$

The effects of $T_o(p)$ and $F_o(p) \neq 0$ can be obtained by superposition.
Setting $p=0$ in equation 12 gives the steady-state error

$$\theta_{ss} = \frac{cw_i}{K} \qquad (13)$$

With the effects of $T_o(t)$ and $F_o(t)$ considered

$$O_{ss} = \frac{cw_i + T_o + F_o}{K} \qquad (14)$$

Similarly in equation 9 with $\theta_i(p) = \theta_i$

$$\theta_{ss} = \frac{T_o + F_o}{K} \qquad (15)$$

In determining stability and transient response of a servomechanism, it is convenient to use some standard input function and then to compare the errors obtained using different controller parameters. A very useful and practical input function of that type is constant velocity, w_i, applied to the input at $t=0$ and held at that value thereafter. This is the case described by equation 12 for the simple-error type of controller. Rewriting equation 12 in terms of $r = \frac{c}{c_c} = \frac{c}{2\sqrt{IK}}$, the ratio of actual to critical damping, and $w_n = \sqrt{\frac{K}{I}}$ the undamped natural frequency of the system yields a more general solution. Then

$$\theta(p) = \frac{(p+2rw_n)w_i}{p+2rw_np+w_n^2} \qquad (16)$$

The solutions for equation 16 obtained by operational methods are

$r<1$

$$\frac{\theta(t)}{\theta_{osc}} = r\left(1 - e^{-rw_nt}\left(\cos\sqrt{1-r^2}\,w_nt + \frac{2r^2-1}{2r\sqrt{1-r^2}}\sin\sqrt{1-r^2}w_nt\right)\right) \qquad (17)$$

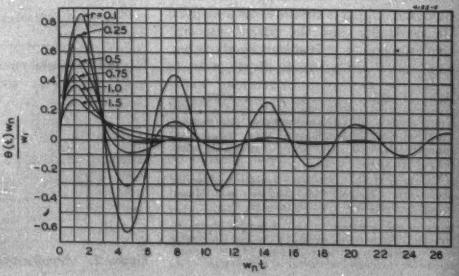

Figure 4. Response curves of error-plus-error-rates servomechanism with no viscous damping and (1-a) held constant

$r=1$

$$\frac{\theta(t)}{\theta_{ssc}}=1-e^{-w_n t}\left(1+\frac{w_n t}{2}\right) \tag{18}$$

$r>1$

$$\frac{\theta(t)}{\theta_{ssc}}=r\left(1-e^{-rw_n t}\left(\cosh\sqrt{r^2-1}w_n t+\frac{2r^2-1}{2r\sqrt{r^2-1}}\sinh\sqrt{r^2-1}w_n t\right)\right) \tag{19}$$

θ_{ssc} is the steady-state error with critical damping and is equal to $2w_1/w_n$. $\theta_{ssc}r=2rw_1/w_n$ and checks θ_{ss} in equation 13. Figure 3 gives $\theta(t)/\theta_{ssc}$ as the ordinate and $w_n t$ as the abscissa, for different values of r. Since both $\theta(t)/\theta_{ssc}$ and w_n are dimensionless and neither contains r, the curves shown in Figure 3 give both the relative magnitude and duration of the transient errors. Figure 3 is similar to the curves given by Hazen,[4] with the exception that different dimensionless parameters which give a truer picture of transient duration were used. As expected Figure 3 shows that when the damping ratio, r, is increased, the oscillation about the steady-state position is reduced, although the time initially to approach the steady-state error is increased. If a fairly large initial overshoot can be tolerated, small damping ratios may give satisfactory performance because of their correspondingly lower steady-state errors.

The prime difficulty with a regulator of this type occurs because the damping torque is proportional to speed. Consequently, at high operating speeds, there is a large amount of power being dissipated in the damper. This loss can be tolerated in low-power systems; however, high-power systems require other means of obtaining stable operation. As is usual in design, compromise is necessary. High values of r are desired to prevent large transient overshoot, yet these same values bring about an increase in the steady-state error and damping power loss.

Error-Plus-Error-Rates Controller

Examination of equation 10 shows that to overcome the disadvantages of the simple-error controller a positive term in p and a negative term in p^2 are desired in the denominator. The positive term will provide damping to the system without increasing the steady-state error or damping loss for a constant-velocity input,

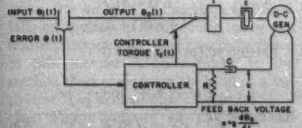

Figure 5 Schematic representation of error-plus-RC-output-feedback servomechanism

since both are dependent only on c. The negative term in p^2 will minimize inertia effects. Such a controller would give $f(p)$ in equation 10 the form,

$$f_c(p)=-ap^2+bp+K \tag{20}$$

and

$$T_c(t)=-a\frac{d^2\theta}{dt^2}+b\frac{d\theta}{dt}+K\theta \tag{21}$$

If equation 1 and equation 7 are used, the differential torque equation can be written as

$$I\frac{d^2\theta_1}{dt^2}+c\frac{d\theta_1}{dt}+T_o(t)+F_o(t)=(I-a)\frac{d^2\theta}{dt^2}+(b+c)\frac{d\theta}{dt}+K\theta \tag{22}$$

Rewritten in operational form

$$\theta(p)=\frac{(mp^2+2frw_n p)\theta_i(p)+(1-m)pw_1+T_o(p)+F_o(p)}{p^2+2rw_n p+w_n^2} \tag{23}$$

with the initial boundary values, $(1-m)pw_1$ showing up as an external torque and where

$$m=\frac{I}{I-a},\quad f=\frac{c}{b+c},\quad r=\frac{b+c}{2\sqrt{(I-a)K}},\quad w_n=\sqrt{\frac{K}{I-a}}$$

With $p\theta_i(p)=w_1$ and $T_o(p)=F_o(p)=0$ equation 23 becomes

$$\theta(p)=\frac{(p+2frw_n)w_1}{p^2+2rw_n p+w_n^2} \tag{24}$$

Solutions by operational methods give

$r<1$

$$\frac{\theta(t)}{\theta_{ssc}}=r\left(1-e^{-rw_n t}\left(\cos\sqrt{1-r^2}w_n t+\frac{2fr^2-1}{2fr\sqrt{1-r^2}}\sin\sqrt{1-r^2}w_n t\right)\right) \tag{25}$$

$r=1$

$$\frac{\theta(t)}{\theta_{ssc}}=1-e^{-w_n t}\left(1+w_n t-\frac{w_n t}{2f}\right) \tag{26}$$

$r>1$

$$\frac{\theta(t)}{\theta_{ssc}}=r\left(1-e^{-rw_n t}\left(\cosh\sqrt{r^2-1}w_n t+\frac{2fr^2-1}{2fr\sqrt{r^2-1}}\sinh\sqrt{r^2-1}w_n t\right)\right) \tag{27}$$

Where

$$\theta_{ssc}=\frac{2fw_1}{w_n}$$

Most designers strive to make c as small as possible so that steady-state error for constant velocity input is minimized. The solutions of equation 24 with $c=f=0$ are

$r<1$

$$\frac{\theta(t)w_n}{w_1}=\frac{e^{-rw_n t}}{\sqrt{1-r^2}}\sin\sqrt{1-r^2}w_n t \tag{28}$$

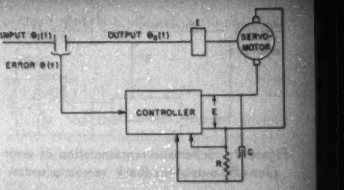

Figure 6. Schematic representation of error-plus-negative-RC-feedback servomechanism

$r=1$

$$\frac{\theta(t)w_n}{w_1}=w_n te^{-w_n t} \tag{29}$$

$r>1$

$$\frac{\theta(t)w_n}{w_1}=\frac{e^{-rw_n t}}{\sqrt{r^2-1}}\sinh\sqrt{r^2-1}w_n t \tag{30}$$

The foregoing equations are particularly useful because they result in simple transient solutions to which the steady-state error for $f\to 0$ can be added without any appreciable inaccuracy. Figure 4 is a plot of $\frac{\theta(t)w_n}{w_1}$ against $w_n t$ for different values of r with $(I-a)$ held constant. It should be noted carefully that for stability $a<I$, since the first criterion of stability is that all coefficients be positive. Again as in Figure 3, the abscissa, $w_n t$; does not contain r so that it truly represents transient durations for variations of r. Figure 4 illustrates quite clearly the compromise involved in derivative damping:

(*a*). Transient duration may be decreased at the expense of peak error.

(*b*). Transient peaks may be decreased by providing a controller capable of delivering high values of derivative damping. This usually involves a more elaborate controller.

As difficult as it is to obtain high value of first derivative damping reliably, the problem is extremely more difficult in obtaining a component proportional to p^2. Usually one takes the values of a that can be obtained and has little control over its magnitude.

Error Controller With RC-Output Feedback

The difficulty of obtaining economically quantities accurately proportional to error change has led to a wide practice of using a resistor–capacitor network across a voltage proportional to the output speed, $d\theta_o/dt$, to obtain antihunt. A common system is to use a d-c tachometer generator directly connected to the output drive. A schematic diagram of a system of this type is shown in Figure 5. Neglecting load and friction torque, torques may be equated as follows:

$$I\frac{d^2\theta_o}{dt^2}+c\frac{d\theta_o}{dt}=T_c(t) \tag{31}$$

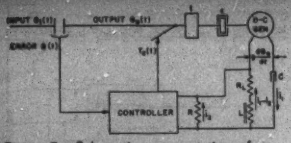

Figure 7. Schematic representation of error-plus-*LRC*-output-feedback servomechanism

Two sets of initial conditions have to be assumed, because different transient responses are obtained when the output velocity function $p\theta_i(p)$ is taken as an acceleration or deceleration. This is caused by the charge on the capacitor, C, for a steady-state velocity The two sets of conditions assumed are:

A. At $t=0$

$$\theta=\theta_i=\theta_o=0$$

$$\frac{d\theta}{dt}=\frac{d\theta_i}{dt}=\frac{d\theta_o}{dt}=0$$

$$\left(\frac{1}{C}\int i\,dt\right)_{t=0}=0 \qquad (32)$$

B. At $t=0$

$$\frac{d\theta}{dt}=\theta_o=0$$

$$\theta_i=\theta=\frac{cw_1}{K}$$

$$\frac{d\theta_i}{dt}=\frac{d\theta_o}{dt}=w_1$$

$$\left(\frac{1}{C}\int i\,dt\right)_{t=0}=gw_1 \qquad (33)$$

The solutions for $\theta(p)$ using boundary conditions (equations 32 and 33) are identical with the exception that the initial values given by equation 33 show up as an external torque. $C_0(p)$ in equation 6. Thus as derived in equations 56 and 60.

$$O(p)=\theta_o(p)$$

$$f_o(p)=\frac{1}{Ip^2+cp+\dfrac{K_2RCgp^2}{1+RCp}}$$

$$C(p)=K\theta(p) \qquad (34)$$

$$E(p)=\theta(p)$$

$$f_c(p)=K$$

$C_0(p)=0$ using equation 32

$$C_0(p)=\left(I+\frac{K_2RCg}{1+RCp}\right)gw_1 \text{ using equation 33}$$

The solution for $\theta(p)$, using equation 32, is given by equation 57 as

$$\theta(p)=\frac{\left(Ip^2+cp+\dfrac{K_2RCgp^2}{1+RCp}\right)\theta_i}{Ip+cp+\dfrac{K_2RCgp^2}{1+RCp}+K}(p) \qquad (35)$$

Letting $p\theta_i(p)=w_1$ at $t=0$

$$\theta(p)=\frac{\left(p^2+hp+\dfrac{c}{RCI}\right)w_1}{p^3+hp^2+\left(\dfrac{c}{RCI}+\dfrac{K}{I}\right)p+\dfrac{K}{RCI}} \qquad (36)$$

where

g = generator constant, volts per radian per second

K_2 = controller constant, foot-pound per volt

$$h=\frac{1}{RC}+\frac{K_2g}{I}+\frac{c}{I}$$

The corresponding solution for $\theta(p)$ using equation 33 is given by equation 61 as

$$\theta(p)=\frac{\left(Ip^2+cp+\dfrac{K_2RCgp^2}{1+RCp}\right)\theta_i(p)-\left(I+\dfrac{K_2RCg}{1+RCp}\right)gw_1}{Ip^2+cp+\dfrac{K_2RCgp^2}{1+RCp}+K} \qquad (37)$$

If at $t=0$, $p\theta_i(p)$ is instantaneously made zero, $\theta_i(p)$ remains at the value cw_1/K and

$$\theta(p)=\frac{\left(p^3+hp^2+\dfrac{c}{RCI}p\right)\dfrac{cw_1}{K}-\left(p+h-\dfrac{c}{I}\right)gw_1}{p^3+hp^2+\left(\dfrac{c}{RCI}+\dfrac{K}{I}\right)p+\dfrac{K}{RCI}} \qquad (38)$$

The steady-state error for constant velocity input, w_1, is still cw_1/K as it was for the simple-error case. To reduce this error, c is made as small as possible. The case with $c=0$ is of importance and reduces both equations 36 and 38 to the same value with the exception of sign. With the positive sign

$$\theta(p)=\frac{\left(p+\dfrac{1}{RC}+\dfrac{K_2g}{I}\right)gw_1}{p^3+\left(\dfrac{1}{RC}+\dfrac{K_2g}{I}\right)p^2+\dfrac{K}{I}p+\dfrac{K}{RCI}} \qquad (39)$$

For $\theta(t)$ to be damped the product of the second and third denominator term coefficients must exceed the first and fourth term coefficient product. This

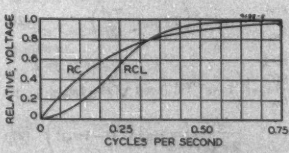

Figure 8. Absolute voltage comparison of *RC* and *LRC* antihunt circuits

$R=200{,}000$ $\quad R_L=100{,}000$

$C=3$ microfarads $\quad L=20{,}000$ henrys

requires $K_2RCg>0$ which is a result that easily could have been anticipated. Solutions for $\theta(t)$ from equations 36, 38 and 39 may be obtained by general methods. However, in many cases, it is easier to assign specific values to the constants, find the roots of the equation by a method with which one is most familiar, and obtain several particular solutions by operational methods, rather than a general solution. If c arbitrarily is made zero only in the denominator of equations 36 and 38, equations result which contain a steady-state velocity error yet do not derive any damping from that energy loss. This represents the case of a d-c motor with thyratron armature control. Here we have a velocity error, because a definite armature voltage must be maintained for constant velocity, and yet no decelerating damping because of the rectifier characteristic of the thyratrons.[5,6]

The big disadvantage of using *RC* output damping is that it retards acceleration response.

$\theta(p)$ for Error Controller With Negative RC Feedback

Typical of the system outlined in Figure 6, is a Ward-Leonard control system with the generator included in the controller. E of Figure 6 then corresponds to the variable voltage of the Ward-Leonard system. The well-known equation for armature current in a d-c motor with constant excitation is

$$i_a=\frac{E-g\dfrac{d\theta_o}{dt}}{Ra}$$

With load torque neglected the accelerating torque is proportional to i_a or

$$C_1i_a=\frac{EC_1-gC_1\dfrac{d\theta_o}{dt}}{Ra}=I\frac{d^2\theta_o}{dt^2} \qquad (40)$$

By following the procedure outlined in the Appendix, and using conditions in equations 32 and 33 again, one finds

$$f_o(p)=\frac{1}{Ip^2+cp}$$

$$C(p)=\frac{K(1+RCp)\theta(p)}{1+RC(1+K_2)p} \qquad (41)$$

$$f_c(p)=\frac{K(1+RCp)}{1+RC(1+K_2)p}$$

$C_0(p)=0$ using equation 32

$$C_0(p)=\left(I+\frac{cK_2RC}{1+RC(1+K_2)p}\right)gw_1 \text{ using equation 33}$$

Use of conditions in equation 32, substitution in equation 6 yields

$$\theta(p)=\frac{(Ip^2+cp)\theta_i(p)}{Ip^2+cp+\dfrac{K(1+RCp)}{1+RC(1+K_2)p}}$$

Letting $p\theta_i(p)=w_1$ at $t=0$

$$\theta(p)=\frac{\left(p^2+\left(h_1+\dfrac{c}{I}\right)p+\dfrac{h_1c}{I}\right)w_1}{p^3+\left(h_1+\dfrac{c}{I}\right)p^2+\left(\dfrac{RCK}{I}+\dfrac{c}{I}\right)h_1p+\dfrac{Kh_1}{I}} \qquad (42)$$

where

$$h_1 = \frac{1}{RC(1+K_3)}$$

Use of conditions in equation 33 and substitution in equation 6 yield

$$\theta(p) = \frac{(Ip^2+cp)\theta_i(p) - \left(I + \frac{(cK_3RC)}{1+RC(1+K_3)p}\right)pw_1}{Ip^2+cp+\frac{K(1+RCp)}{1+RC(1+K_3)p}} \quad (43)$$

If at $t=0$, $p\theta_i(p)$ is instantaneously made zero, $\theta_i(p)$ remains at the value $\frac{cw_1}{K}$ and

$$\theta(p) = \frac{\left[\left(p^3+\left(h_1+\frac{c}{I}\right)p^2+\frac{h_1cp}{I}\right)\frac{cw_1}{K} - \left(p+h_1+\frac{cK_3}{I(1+K_3)}\right)pw_1\right]}{p^3+\left(h_1+\frac{c}{I}\right)p^2+\left(\frac{RCK}{I}+\frac{c}{I}\right)h_1p+\frac{Kh_1}{I}} \quad (44)$$

As was the case with output damping, $\theta(t)$ can be found by operational methods. This system of obtaining stability also is detrimental to acceleration response because it depends for its operation on slowing up the appearance of the voltage, E.

Error Controller With LRC Output Feedback

With a feedback circuit such as used in Figure 7, rather than one as used in Figure 5, the advantage of a faster acceleration response without sacrifice of antihunt is obtained. The simplest way to show what results is to plot the absolute value of the voltage appearing across R against frequency for both the RC and LRC cases. Figure 8 gives such a comparison. In the lower-frequency range the LRC circuit gives less negative feedback, consequently, acceleration rates are higher. However, in the higher-frequency ranges the negative feedback of both the LRC and RC circuits are about the same. By selecting the value of L, R, and C the frequency at which the feedback voltage first reaches its peak can be made the natural hunting frequency of the system. If this be done, the system is damped because of high negative feedback at hunting frequency, and yet acceleration response is not too badly affected because the amount of negative feedback falls off rapidly at frequencies below the hunting frequency. Using an inductance in this manner is quite similar to the method used to increase the gain of a capacitor-coupled amplifier at high frequencies. Figure 7 shows only one section of this type of high-pass filter. More than one section gives even a sharper change from low to high negative-feedback values than that shown in Figure 8. The solution of the LRC problem in operational form is obtained by following the same procedure outlined in the appendix. Then

$$i_o(p) = \frac{1}{Ip^2+cp+\frac{K_3RC_g(R_L+Lp)p^2}{R+R_L+Lp+RCp(R_L+Lp)}} \quad (45)$$

$$C(p) = K\theta(p)$$

$$f_c(p) = K$$

$C_o(p) = 0$ (using equation 32)

$$C(p) = \left(I + \frac{K_3RC_gR_L+Lp}{R+R_L+Lp+RCp(R_L+Lp)}\right)pw_1$$

When equations 32 and 45 are substituted into equation 6 and one lets $p_i\theta(p) = w_1$ at $t=0$

$$\theta(p) = \frac{\left(Ip+c+\frac{K_3RC_g(R_L+Lp)p}{R+R_L+Lp+RCp(R_L+Lp)}\right)w_1}{Ip^2+cp+\frac{K_3RC_g(R_L+Lp)p^2}{R+R_L+Lp+RCp(R_L+Lp)}+K} \quad (46)$$

When equations 33 and 45 are used similarly and substituted into equation 6, then if at $t=0$ w_1 instantaneously is made zero, $\theta(p)$ remains at cw_1/K and

$$\theta(p) = \frac{\left(Ip^2+cp+\frac{K_3RC_g(R_L+Lp)p^2}{R_L+R+Lp+RCp(R_L+Lp)}\right)\frac{cw_1}{K} - \left(I+\frac{K_3RC_g(R_L+Lp)}{R+R_L+Lp+RCp(R_L+Lp)}\right)pw_1}{Ip^2+cp+\frac{K_3RC_g(R_L+Lp)p^2}{R_L+R+Lp+RCp(R_L+Lp)}+K} \quad (47)$$

Time Delays

All the equations given so far have neglected time delays. In systems in which this delay time is small compared to the natural period, the equations can be used as given. However, when long relative delay times are involved, they must be introduced. In the familiar case of current response of a series LR circuit,

$$i = \frac{1}{1+\frac{L}{R}p}\cdot\frac{E}{R}$$

and L/R occurring in the denominator can be thought of as a time delay, t. The steady-state value, E/R, has already been included in the constants K and K_3 used in the response equations. Therefore, in order to introduce time delay the affected term merely should be multiplied by $\frac{1}{1+tp}$. If more than one time delay is to be included, by a similar line of reasoning the affected term is multiplied by

$$\frac{1}{(1+t_1p)(1+t_2p)\ldots(1+t_np)} \quad (48)$$

Thus for the Ward-Leonard system which contains both field and armature time delays, equation 35 becomes

$$\theta(p) = \frac{\left(Ip^2+cp+\frac{K_3RC_gp^2}{(1+t_fp)(1+t_ap)(1+RCp)}\right)\theta_i(p)}{Ip^2+cp+\frac{K_3RC_gp^2}{(1+t_fp)(1+t_ap)(1+RCp)}+\frac{K}{(1+t_fp)(1+t_ap)}}$$

Similarly equations including time delay could be written for all the response equations given. Rationalizing an equation of the type given in equation 49 results in a denominator containing a fifth degree equation in p. Finding the roots of that equation and then using operational methods gives the solution for $\theta(t)$. The increasing complexity of the solution for $\theta(p)$, when several time delays are included, has resulted in a practice of finding the roots of the denominator equation and evaluating the stability by the damping factors of the roots.[7,8]

Types of Input Functions

All the response equations given have used a unit function as the input. This is a simple function by which the response for the different systems of control can be directly compared. However, it is not the only one that can be used. If the response to a sine, constant acceleration, or any other input is desired, it is necessary merely to substitute the correct operational form of the sine or constant acceleration input for $\theta_i(p)$ and proceed with the solution exactly as if w_1 had been substituted for $p\theta_i(p)$. This provides a method for finding the exact response to a known input function. Most problems, however, involve random inputs, consequently a good method of comparison such as is provided by the unit function is adequate.

Summary

The previous example of a remotely located gun turret continuously following a hand-operated sight serves well to illustrate the method and equations given. In the design of such a system it is desired that the gun stay in line with the sight within close limits. It is also desired that the gun deviate as little as possible and realign itself as quickly as possible after some disturbance has moved the sight. Thus, the sight position corresponds to $\theta_i(t)$ and the difference in their respective positions at any time to $\theta(t)$. Finding $\theta(t)$ helps enormously in designing a control system, for not only is it

the error equation but also it shows what values such fundamental parameters as the stiffness of the system, K, the viscous damping, c, the inertia, I, and the antihunt feedback constant, K_2, must have in order to keep errors within desired limits. The error equation in operational form $\theta(p)$, has been given for a number of different systems of control, any of which will do the job. Each system accomplishes the basic purpose of keeping the gun turret aligned with the sight. However, the transient and steady-state errors may be quite different for similar values of stiffness, damping, inertia, and so forth. It is the problem of the designer to evaluate the complexity of any system against its merit and then select the simplest system that will perform within desired limits. Setting p equal to zero in any of the derived equations for $\theta(p)$ gives steady-state errors for angular displacement and velocity. From these can be selected values of viscous damping and stiffness which will give a small enough steady-state error to meet a given specification. Integrating $\theta(p)$ operationally gives $\theta(t)$, the transient error response. From the resulting equation values of antihunt, K_2, or error rate of change, b, can be selected which will limit the peak error to the desired value.

The method shown for obtaining these criterion equations for $\theta(p)$, consists of breaking the servomechanism up into its component parts, obtaining the controller and output response functions, and then obtaining $\theta(p)$ by using the general servomechanism equation 6. This is a systematic procedure for handling an unwieldy problem. Further refinement can be made by introducing time delays and varied input functions. Although all particular solutions obtained by use of equation 6 were for angular position regulators, equation 6 is entirely general. Therefore servomechanisms to control such quantities as voltage speed, pressure, and so forth are represented by equation 6. Particular solutions obtained for the angular position servomechanism can be applied to servomechanisms controlling other quantities by using unit analogy.

Appendix. $\theta(t)$ for Error Controller With RC Output Feedback

In order to calculate the feedback component of torque, it is first necessary to find the voltage appearing across R of Figure 5, as a function of time. The series voltage summation is

$$iR+\frac{1}{C}\int idt=g\frac{d\theta_0}{dt} \tag{49}$$

By standard operational methods this can be rewritten as

$$Ri(p)+\frac{i(p)}{Cp}+\left(\frac{1}{C}\int idt\right)_{t=0}= gp\theta_0(p)-g\theta_0(p)_{t=0} \tag{50}$$

When conditions from equation 32 are used, the voltage appearing across R, is

$$Ri(p)=\frac{RCgp^2\theta(p)}{1+RCp}$$

which, when fed back into the controller negatively, gives an output torque component

$$-K_2Ri(p)=-\frac{K_2RCgp^2\theta_0(p)}{1+RCp} \tag{51}$$

where K_2 is the controller constant with units of foot-pounds per volt. Then for a controller which also has a simple error component, the controller torque is

$$Tc(p)=K\theta(p)-\frac{K_2RCgp^2\theta(p)}{1+RCp} \tag{52}$$

With load, $T_o(t)$, and friction, $F_o(t)$, neglected, the differential torque equation is

$$I\frac{d^2\theta_0}{dt^2}+c\frac{d\theta_0}{dt}=T_c(t) \tag{53}$$

When operational methods and boundary conditions from equation 32 are used

$$Ip^2\theta_0(p)+cp\theta_0(p)=Tc(p)=K\theta(p)-\frac{K_2RCgp^2\theta_0(p)}{1+RCp} \tag{54}$$

This can be rewritten in the form,

$$\theta_0(p)=\left(\frac{1}{Ip^2+cp+\dfrac{K_2RCgp^2}{1+RCp}}\right)K\theta(p) \tag{55}$$

When equations 4 and 5 are used, the following comparisons can be made:

$$O(p)=\theta_0(p)$$

$$f_o(p)=\frac{1}{Ip^2+cp+\dfrac{K_2RCgp^2}{1+RCp}} \tag{56}$$

$$C(p)=K\theta(p)$$

$$E(p)=\theta(p)$$

$$f_c(p)=K$$

By using equations 6 and 56 and rationalizing, one obtains

$$\theta(p)=\frac{\left(Ip^2+cp+\dfrac{K_2RCgp^2}{1+RCp}\right)\cdot(p)}{Ip^3+cp+\dfrac{K_2RCgp^3}{1+RCp}+K} \tag{57}$$

If the same procedure previously outlined is followed and conditions from equation 33 are used,

$$T_c(p)=K\theta(p)-\frac{K_2RCg(p^2\theta_0(p)-p\omega_i)}{1+RCp} \tag{58}$$

Use equation 56, boundary conditions of equation 33 and solve for $\theta(p)$:

$$\theta_0(p)=\left(\frac{1}{Ip^2+cp+\dfrac{K_2RCgp^2}{1+RCp}}\right)\times\left[K\theta_0(p)+\left(I+\frac{K_2RCg}{1+RCp}\right)p\omega_i\right] \tag{59}$$

Comparison with equation 5 gives

$$C_o(p)=\left(I+\frac{K_2RCg}{1+RCp}\right)p\omega_i \tag{60}$$

in addition to the previous relations, which were established in equation 56. Thus the initial boundary conditions occur as external torques in the general equation. By using equations 6, 56, and 60 and rationalizing, we obtain

$$\theta(p)=\frac{\left(Ip^2+cp+\dfrac{K_2RCgp^3}{1+RCp}\right)\theta_i(p)-\left(I+\dfrac{K_2RCg}{1+RCp}\right)p\omega_i}{Ip^3+cp+\dfrac{K_2RCgp^3}{1+RCp}+K} \tag{61}$$

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Design Considerations of 400-Cycle Aircraft Motors

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SEVERAL papers have been presented describing the reason for the selection of 400-cycle three-phase service for motors aboard aircraft. In view of the fact that the decision has been made to use 400 cycles, the purpose of this paper is to present some of the motor-design problems to the men who must write the specifications for these motors. A better general understanding of the performance to be expected from 400-cycle induction motors will help both the aircraft electrical engineer and the motor designer.

An electric system such as used on an airplane must be designed as a unit. The generating system is never sufficiently large to permit the assumption of uniform voltage and frequency under all conditions. The need for dependability requires the use of some reliable overload-protection device which must be considered as part of the motor. The type of load, which may involve a large variation in torque during the duty cycle, must be completely understood by the motor designer. Also, the motor control must be such as to insure reliable motor operation. The need for co-operation between the engineers working on these varied but intimately related problems cannot be too highly emphasized.

Only those characteristics of 400-cycle motors which differ radically from characteristics of the 24-volt d-c motors used in the past will be discussed. Mechanical problems will not be discussed, although new mechanical problems have appeared due to the possibility of speeds up to 24,000 rpm.

First we will list the requirements of the airplane designer and then point out some of the problems faced by the motor designer to meet these requirements.

1. The first requirement of the airplane designer, so obvious that it is frequently overlooked or subordinated to other requirements, is dependability. The motor must do the job assigned to it unfalteringly on each occasion when it is needed during the period between servicing. In this respect the induction motor has definite obvious advantages over the 24-volt d-c motor. These include simpler windings, freedom from commutation, and fewer parts.

2. The weight must be minimum consistent with dependability.

3. The motor must be capable of doing its job when the maximum voltage is ten per cent above or ten per cent below rating, and when the frequency is five per cent above or below rating.

4. The requirements for starting torque in proportion to full-load torque will vary considerably, but should ordinarily not be below 120 per cent of full-load torque.

5. The maximum torque permissible is determined by the airplane structure and is sometimes as low as 120 per cent of the full-load torque.

6. If the motor is to run continuously, its efficiency may be as important as its weight because of the added weight of fuel which must be carried to run a less efficient motor.

7. It is desirable to have a high power factor to reduce line losses and generating capacity required.

8. The same ambient temperature, humidity, altitude, and vibration specifications apply to 400-cycle motors as were used with the d-c motors.

These, then, are the primary requirements of the airplane designer which affect the motor designer. The generalization that high speed means less weight per horsepower will now be investigated by considering the results of running a familiar one-horsepower 60-cycle four-pole induction motor from a 400-cycle power supply.

The motor selected is one having quite common performance characteristics. The starting torque is 200 per cent of full-load torque, and the maximum or breakdown torque is 300 per cent of full-load torque. The efficiency is 80 per cent and the slip at full load is four per cent. The motor being considered differs from an ordinary industrial motor in that better materials are used and precautions are taken to prevent interlamination losses. The motor is totally enclosed so that the analysis will not be confused too much by increased friction and windage. Otherwise, the motor is a conventional one with a well proportioned lamination and normal performance.

The full-load torque of any motor is the maximum torque which can be developed by the motor for the rated time of operation without exceeding a safe operating temperature. This is the case in all motors, although the interpretation of "safe operating temperature" will be revised drastically when the motor is used aboard an airplane. For purposes of comparison let us assume that the same cooling is used on 400 cycles as on 60 cycles, that the same temperature rise is permitted, and therefore the same total losses in the motor are permissible.

Let us now consider how this motor will operate on 400-cycle service. In order to keep the flux the same, the motor must be operated on a voltage 6.7 times higher than the 60-cycle voltage. That is, the voltage must be increased in proportion to frequency. The synchronous speed, of course, increases from 1,800 rpm to 12,000 rpm. The magnetizing current increases only slightly. The motor resistance is not changed at all by operating the motor on 400 cycles; however, the leakage reactance increases in proportion to the frequency, that is 6.7 times.

The rated torque is determined by the losses, and is practically the same as on 60 cycles. Therefore, the horsepower rating is increased by 6.7 times. The breakdown torque has increased by 70 per cent to over 500 per cent of full-load torque. This follows from the increase of voltage proportional to frequency, together with a much smaller increase in circuit impedance.

Since the motor produces the same full-load torque with the same losses, but at 6.7 times the speed, the efficiency has been increased considerably. The efficiency has come up from 80 per cent to 95 per cent or better.

The slip at full-load torque is reduced from four per cent to 0.6 per cent. This can be understood by picturing what happens from the standpoint of the rotor. The torque is produced by the action of the rotor current on the rotating flux produced by the field. By operating the motor on 400 cycles instead of 60 cycles, the magnitude of the flux is not altered; only the speed of the rotating flux has been changed. On 60 cycles, with a slip of four per cent or 72 rpm, the rotor bars were cutting the flux at such a speed as to produce sufficient rotor current to develop full-load torque. On 400 cycles the flux is rotating 12,000 rpm; however, a difference in speed of 72 rpm between the rotating field and the rotor still produces sufficient rotor current to develop full-load torque. The current in the rotor under load depends on the voltage induced in the bars, which in turn depends on the rate of cutting flux.

The slip at which maximum torque is obtained will also be very small. Maximum torque on 60 cycles is obtained at 30 per cent slip, the slip for maximum torque on 400 cycles will be near five per cent. The fact that all torques from zero to maximum are produced within a range of five per cent is useful in synchronizing actuators located at remote parts of the airplane.

So far we have presented a very satis-

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factory picture of increased performance in horsepower per pound by increasing the frequency. One disturbing factor remains to be considered. This factor is the starting torque. A 60-cycle motor designed for maximum horsepower per pound has adequate starting torque. However, a 400-cycle motor designed for maximum efficiency and horsepower per pound has a relatively small starting torque. Redesign by changing the circuit constants of the 400-cycle motor results in a loss of efficiency and consequent increase in weight per horsepower.

The starting torque is proportional to the I^2R loss in the rotor divided by the synchronous speed. Returning to the example, the locked rotor current on 400 cycles is 40 per cent higher than the current on 60 cycles. The I^2R loss will approximately double, while the synchronous speed is increased 6.7 times; the torque, then, will be reduced 3.3 times. This means that instead of 200 per cent starting torque the motor now develops 60 per cent starting torque. In actual practice the rated full-load torque of the motor could be increased considerably by inproving the cooling and by raising the allowable temperature limit. This increase in rating only serves to lower the percentage starting torque. This difficulty is a major problem in the design of 400-cycle motors for aircraft use.

This example has been purposely selected to show the difficulty clearly. This difficulty is not nearly so pronounced in very small motors because the leakage reactance is relatively small in comparison to the resistance, and the majority of motors used aboard aircraft are small. The problem remains in some degree, however, and must be overcome. Figure 1 illustrates the example. Speeds in percentage of synchronous are plotted as ordinates and torques are plotted as abscissas. The motor on 400 cycles produces the same torque at rated horsepower as on 60 cycles, but produces much less torque at standstill.

We shall now consider ways of increasing this usually inadequate starting torque. As previously stated, the starting torque varies directly as the I^2R loss in the rotor and inversely as the synchronous speed. To increase the torque, the rotor current or the rotor resistance, or both, must be increased. Table I shows the comparative values obtained in operating our one-horsepower motor on 60 cycles and on 400 cycles, together with the effect of increasing the rotor resistance. In many aircraft applications it may be desirable to produce the high maximum torque at standstill. In the example chosen this would be accomplished by increasing the rotor resistance about 20 times. The penalty, however, would lie in the necessary decrease in rated torque due to the heating in the high-resistance rotor. The reduction in rated torque would be by a factor of approximately three. With the starting torque 500 per cent of the motor's previous rating, and the rating reduced by a factor of three, the starting torque would now be about 1,500 per cent of rated.

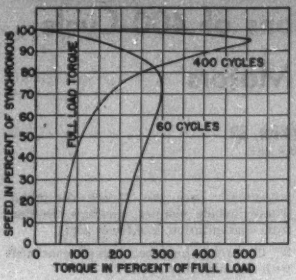

Figure 1. Speed–torque curves

Although this large starting torque is obtainable, a reasonable value of 200 per cent starting torque can be obtained by increasing the rotor resistance without much sacrifice in rated torque. In the example chosen, a threefold increase in rotor resistance will achieve this result with a net decrease in rated torque of 20 per cent.

A second method of increasing the starting torque is by raising the starting current by decreasing the reactance. The reactance is a function of slot size and proportions, and air gap. Let us assume that the reactance could be cut in half. This would approximately double the starting current, and therefore give four times the starting torque. This method would not affect the losses at full load appreciably. The over-all effect, however, would usually be to decrease the power factor through increased magnetizing current. This method of increasing starting torque has possibilities, but leads to higher starting currents and bad power factor.

A third way of increasing the starting torque is to alter the motor so that the resistance or reactance, or both, will vary as the motor comes up to speed. In this classification are included double-cage rotors, external rotor resistance operated through centrifugal switches, and many ingenious devices. The small physical size of aircraft motors makes this method quite difficult, but some desirable solutions will be obtained by this method. In fact, all 400-cycle motors take advantage of some variation in rotor resistance from standstill to full load because of the current distribution due to leakage flux in the rotor bars.

A fourth possibility of increasing the starting torque of the motor is by the use of some mechanical device such as a centrifugally operated clutch which would permit the motor to attain speed before picking up the load.

Economy in weight and efficiency of electrical motors can be obtained by designing the correct load so that large starting torques are not required.

Next in importance to the problem of starting torque is the problem of what to do with the maximum torque developed by the induction motor. As noted in the list of requirements, the airplane designer uses such low factors of safety that the maximum torque applied to the load must be definitely limited, sometimes to as little as 20 per cent in excess of the required torque. This same problem gave some difficulty in d-c motors because of voltage and temperature variations. The series motor, however, develops maximum torque at standstill, which is very desirable for most aircraft applications. We have seen that altering the induction motor so that the maximum torque is obtained at standstill results in lower efficiency and consequent increase in pounds per horsepower. In any case, the specified range of voltage and frequency will cause variations in the maximum torque, probably in excess of 20 per cent.

Therefore, it is necessary either to build the structures sufficiently heavy to withstand considerable maximum torque or to use some method of limiting the torque other than motor design. In d-c motors a slip clutch is used successfully since the speed drops off rapidly with increased torque. With an efficient 400-cycle motor the speed at maximum torque is very high, and if a slip clutch is used the motor will heat very rapidly. The thermal protecting device must then operate to open the circuit. Probably a better solution would be the use of a switch operated directly by torque which would open the motor circuit. The use of shear pins in some form is another possible solution.

The problem of the wide range of ambient temperatures does not affect the 400-cycle motor in the same way it affects the 24-volt d-c motor. Low temperature decreases the resistance, which in the case of the d-c motor increases the torque. In

Table I. Effect of Rotor Resistance on Motor Rating

Frequency	Rotor Resistance	Rated Load		Maximum Torque		Starting Torque	
		Horsepower	Torque, Pound-Feet	Pound-Feet	Per Cent of Rated	Pound-Feet	Per Cent of Rated
60	1.0	1.0	3.0	9	300	6.0	200
400	1.0	6.7	2.9	16	510	1.8	60
400	20	2.4	1.1	18	1,500	16	1,500
400	2.8	5.2	2.3	16	680	4.8	200

an induction motor, the low temperature decreases the starting torque. This difficulty of decreased torque is of academic interest only, however, since the rotor currents will rapidly bring the motor up to operating temperature.

The humidity requirements are easier to meet with the induction motor. In developing motors for use in such equipment as submersible pumps for the Navy, methods of impregnating stators have been brought to a much higher degree of perfection than ever before. We do not anticipate any difficulty due to humidity as it affects insulation.

Altitude will have no effect on the electrical operation of induction motors, except as it influences rating by changing the cooling. Considerable data on this effect has been obtained in the use of d-c motors, and these data are used in the design of 400-cycle motors.

One difficulty which requires close cooperation between the airplane electrical engineer and the motor designer is the question of line drop. We have frequently encountered difficulty in operating high-frequency motors in wind-tunnel testing. For instance one motor developed about 35 horsepower at 6,000 rpm, from 300-cycle service. The short leads used between the control panel and the motor installed in the model doubled the resistance and reactance of the stator. In other words, the line drop equalled the stator drop. This difficulty can be overcome by including the line characteristics in predicting the motor performance. With minimum-size lines, starting torque may be seriously affected if starting current is high.

There is a tendency among some writers of specifications to avoid the use of gear reductions in favor of multipole motors. An eight-pole one-horsepower motor will be twice as heavy as a four-pole one-horsepower motor operating from the same frequency. In addition, increasing the number of poles tends to lower both the efficiency and the power factor. This undesirable effect is greatly pronounced in motors of small size. In addition, the starting torque is relatively lower.

We might summarize this discussion by saying that the 400-cycle squirrel-cage induction motor has great possibilities for increasing the horsepower per pound. Difficulties to be overcome before these possibilities can be completely realized have been discussed. These difficulties are not insoluble. The company with which the writer is associated and many other electrical designing groups have some solutions to all of these problems, and many more solutions will be found.

We have pointed out the necessity of the closest co-operation between the designer of motor and power-supply equipment, the airplane designer, and the control designer. With this co-operation and a clear understanding of the problems involved, the 400-cycle aircraft power-supply system will be a marked success.

Field Determination of Current-Transformer Errors by the Secondary-Voltage Method

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FOR many years there has been a need for a relatively simple field method for testing bushing current transformers for accuracy.

A paper by A. C. Schwager[4] describes a method of predetermining a current transformer's performance based on its admittance-vector locus. A study of this paper suggested the possibility of developing a method of testing such current transformers in the field.

Explanation of Secondary-Voltage Method

In the method to be described in this paper, progressively increasing voltages are applied to the secondary winding of a current transformer with the primary winding open-circuited. In this condition the current transformer builds up an opposing reactive voltage nearly equal to that applied. Thus, only a relatively small amount of current is allowed to flow in the secondary winding. This "exciting" current is made up of two components, that is, a "magnetizing" component and a "core-loss" component. The purpose of this method is to analyze the "exciting" current into its components with the object of combining them by formula with the normal secondary currents and thereby find the phase-angle errors and ratio correction factors for the current transformer under test at certain secondary current values, such as, 0.5, 1, 2, 3, 4, and 5 amperes. Before starting the test the current transformer should be demagnetized, with its primary winding open-circuited, by gradually increasing the secondary-winding test voltage from zero to 50 or 100 volts and back to zero, taking care to protect the test instruments during this operation.

To analyze the exciting current into its two components it is passed through the current coil of a wattmeter, the potential coil of which is energized first by a test voltage (E_r) which is 90 degrees out of phase with the induced secondary reactive voltage (E_s) and then by another test voltage (E_w) which leads E_r by 90 degrees, or is itself in phase with E_s. The vars measured in the first case, with voltage E_r, hereafter shall be referred to as V, and the watts measured with voltage E_w, as W.

The magnetizing component of the exciting current, or that portion which is used to produce voltage E_s, is equal to V/E_r, and the core-loss component is W/E_w.

Susceptance (B), or amperes of magnetizing component per induced volt, is V/E_rE_s, and conductance (G), or amperes of core-loss component per induced volt, is W/E_wE_s.

The higher the resistance (R) and reactance (X) of the secondary burden through which the current transformer has to force the secondary current, the higher will be the value of secondary voltage (E_s) that has to be induced. Consequently, the greater will be the core losses in producing it.

It is convenient to express the errors of current transformers in terms of the phase-angle error (ϕ) and the ratio correction factor (RCF). The phase-angle error may be expressed in terms of its tangent and the four quantities B, G, X, and R.

$$\text{Tan } \phi = \frac{BR - GX}{1 + BX + GR}$$

Ratio correction factor (RCF) is expressed in terms of the same quantities and is equal to $(1+BX+GR)/\cos \phi$. For angles less than $2^1/_2$ degrees the RCF may be expressed as $1+BX+GR$ with an error of less than one tenth of one per cent.

Figure 1 shows the connections required for making the aforementioned tests.

Description of Equipment and Test Procedure

The regulating transformers furnish a means for adjusting the test voltage. If an autotransformer is used for this purpose care must be taken to disconnect completely the secondary winding of the current transformer from ground, as ordinarily the supply voltage already will be grounded.

Potential from the regulating trans-

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formers is applied to the current-transformer secondary winding and a compensating burden. For a multi-ratio current transformer a ratio, such as 200–5 amperes, is preferably selected for the tests. The errors for other ratios then may be calculated from curve data obtained at the 200–5-ampere ratio. With switch S in the upper position a voltage of 0.1, 0.2, 0.5, 1, and 2 volts is applied by means of a 20–2-volt service transformer. For voltages greater than 2 it may be applied directly with switch S in the down position. Then the steps applied for the test are 5, 10, 20, 50, and even as high as 100 or more volts.

Table I

E_s	V	E_v	W	E_w	V/E_v	W/E_w	E_s/N	B	G
0.1									
0.2									
0.5									
1									
2									
5									
10									
20									
50									
100									

Figure 1. Wiring diagram of equipment for testing a current transformer of known turn ratio by the secondary-voltage loading method

The test equipment is as follows:
Regulating transformer, 120 volts, 60 cycles, manually operated
Step-down transformer, 60 cycles, 20 to 2 volts
Insulating tranformer, 60 cycles, 50 to 50 volts with a very low exciting current, for use as an autotransformer
Compensating burden composed of resistance (R_d) and reactance (X_d)
Double-throw selector switch (S)
Voltmeter 1, 0–150 volts alternating current
Voltmeter 2, of high resistance with 0–1–5–25–125-volt a-c scales
Phase-angle detector with a 150-volt 60-cycle field coil. It is desirable to have the rotor coil, together with its series resistance, wired for the same operating ranges as voltmeter 2 and to be cut into service by the same selector switch
Wattmeter with scale to suit test conditions, but usually with a 100–200-watt scale
Potential-type phase-angle meter, 120 volts, 60 cycles
Phase shifter, 120 volts, 60 cycles, single phase with a range of plus or minus 180 degrees

A compensating burden is introduced into the circuit in order to match the total burden of the current-transformer secondary winding and leads, the wattmeter current coil, and the test leads. The 50–50 volt service transformer is used to subtract this voltage drop, together with the drop across the compensating burden itself, vectorially from the applied voltage (E_s). It thereby secures the true induced secondary voltage (E_s) for use in the phase-angle detector and in indicating voltmeter 2.

Voltmeter 1 is used to determine the values of the voltages (E_v and E_w) that are applied to the wattmeter potential coil when vars (V) and watts (W) are read on the wattmeter.

The phase-angle detector shown in Figure 1 is an electrodynamometer type of instrument equipped with two voltage coils. It has a fixed coil rated 120 volts and a rotor coil which is designed for variable voltages with full-scale ranges of 1, 5, 25, and 125 volts. The inductance of its coils may be neutralized with suitable shunt capacitors.

A phase-angle meter with two voltage elements also is required for the tests. A synchroscope with a 360-degree scale and a light moving element mounted with its shaft in the vertical position can be calibrated in degrees to serve as a phase-angle meter.

During the test the voltage (E_s) is shifted with the small knob on the phase shifter until it lags E_s by 90 degrees, at which time there will be zero deflection on the phase-angle detector. Vars are read as V on the wattmeter, and voltage (E_v) is read and recorded also. Next, the moving element of the phase shifter is rotated counterclockwise until a voltage is obtained that leads E_s by 90 degrees, as indicated by the phase-angle meter. This voltage (E_w) is now known to be in phase with voltage E_s. Maximum deflection of the phase-angle detector occurs at this time. A record is kept of the watts (W) indicated by the wattmeter and of the volts (E_w).

It will be found that, as the voltage is increased from very low values, the readings of both V and W will increase slowly at first and then quite rapidly for the higher-voltage values.

By using a combination wattmeter–varmeter, the 90-degree phase shift is obtained without other adjustments, and the phase-angle meter then may be omitted.

Calculations will be facilitated and repetition of test conditions kept to a minimum if the test quantities are given as in Table I.

It should be noted that $B = V/E_sE_w$ and $G = W/E_sE_w$, where N is the actual turn ratio of the current transformer under test.

Preparation of the Two Characteristic Curves

The values calculated in the last two columns of Table I are plotted vertically against the values of E_s/N on the horizontal scale of log–log cross-section paper. There should be three vertical cycles and at least three horizontal cycles on the log–log paper.

Figure 2 shows typical curves of B and G for a 115-kv bushing current transformer tested at 40 secondary turns and a nominal ratio of 200–5 amperes. From these two curves ratio and phase-angle errors may be calculated for any burden and any ratio within the range of the test data.

The diagonal lines for the various current-transformer ratios are drawn as follows:

1. Draw the diagonal base line for the 200–5-ampere ratio, as shown, between 0.001 on the lower left hand margin and 1.0 on the upper margin.

2. Draw parallel lines starting at distances along the vertical scale equal to the ratio

$$\left(\frac{\text{Actual turn ratio}}{40}\right)^2$$

and along the horizontal scale at distances equal to

$$\left(\frac{40}{\text{actual turn ratio}}\right)^2$$

Application of Characteristic Curves

Since the two characteristic curves are plotted as in Figure 2, the values of B and G and hence the errors may be determined for any current-transformer ratio at any secondary current and burden. For example, at the 100–5-ampere ratio with a secondary burden of $R=0.738$ and $X=0.307$ ohm, with 5 amperes secondary current, the secondary volts (E_s) will be $5\sqrt{0.738^2+0.307^2}$, or 4. For a current-transformer ratio of 100–5 amperes, E_s/N is 4/20 or 0.2. A vertical line is drawn at $E_s/N=0.2$ to intersect the G and B curves as shown. Horizontals from these curves intersect the 100–5-ampere diagonal line at values of 0.091 for G and 0.157 for B. Thus, the phase-angle and ratio errors are found as follows:

$$\text{Tan } \phi = -\frac{BR-GX}{1+BX+GR}$$

$$= \frac{(0.157)\ (0.738)-(0.091)\ (0.307)}{1+(0.157)\ (0.307)+(0.091)\ (0.738)}$$

$$= \frac{0.1160-0.0279}{1+0.0482+0.0672} = \frac{0.0881}{1.1154} = 0.0791$$

$$\phi = +4°\ 31\tfrac{1}{2}'\ \cos\phi = 0.9969$$

$$RCF = \frac{1+BX+GR}{\cos\phi} = \frac{1.1154}{0.9969} = 1.1185$$

It is usually found convenient to list the quantities as shown in Table II.

Conclusions

From the foregoing discussion it is apparent that a current transformer with primary and secondary turns known may be checked in the field at its secondary terminals in a substation if desired. For bushing current transformers an intermediate ratio, such as 200–5 amperes, is chosen and a range of test voltages applied to the secondary winding varying from 0.1 volt to 100 or more volts. It is not necessary to completely disconnect the current transformer from the high-voltage circuit, provided its primary is open-circuited. In this case one side of the current-transformer secondary winding should be kept grounded.

Test equipment may be kept to a minimum, if approximate results are sufficient, by applying the secondary voltage at the current-transformer terminals. The phase shifter, 50–50-volt transformer, compensating burden, and phase-angle detector then may be omitted. The error in this instance will be caused by applying a voltage, E_a, that differs from the induced secondary voltage, E_s, by the voltage drop in the secondary winding and test leads caused by the passage of the test current. If the secondary test voltage is kept below ten volts in testing a bushing-type current transformer of 200–5 amperes, the error in the results from neglecting this difference should be less than two per cent.

From the field data two curves are plotted on log–log cross-section paper with one curve showing the susceptance (B) of the open-circuited current transformer, and the other showing its conductance (G). Values of E_s/N are used for the horizontal scale in each case. Parallel diagonal lines are drawn on the log–log paper to represent all available ratios, and the sheet is then ready for use in determining the ratio and phase-angle errors of any burden at any power factor for any current-transformer ratio, within the limits of the data taken. The RCF in terms of a nominal turn ratio is equal to $\frac{\text{actual turn ratio}}{\text{nominal turn ratio}}$ multiplied by (actual RCF).

For metering use the limits 0.001 to 1.0 for E_s/N at the 200–5-ampere ratio covers most of the required metering ranges for all standard bushing-current-transformer ratios. However, for relay use it would be better in all probability to make the tests at 100–5 or at 50–5 am-

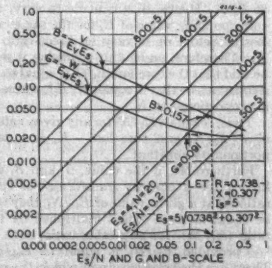

Figure 2. Curves of G and B plotted from test data for a multiratio current transformer at 200–5 amperes

Values of G and B at any secondary burden and any available ratio are determined as indicated by the arrows

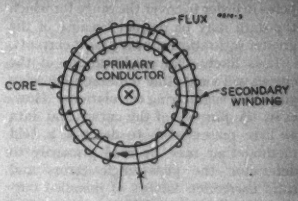

Figure 3. Typical multiratio bushing current transformer

The winding of one ratio only is shown

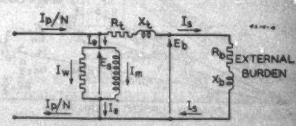

Figure 4. Equivalent circuit of a current transformer in service under load conditions

Summary of the terms used:

R_b = ohms resistance of external secondary burden

X_b = ohms reactance of external secondary burden

R_t = ohms resistance of current-transformer secondary winding. Its effect is the same as if it were connected externally in the circuit as shown

X_t = ohms reactance of current-transformer winding. This is usually so small that it may be neglected

I_w = amperes core loss which = $W/E_s = GE_s$

I_p = amperes primary current

N = turn ratio between secondary and primary turns of current-transformer

I_p/N = equivalent primary current (amperes) on a 1-to-1 ratio basis

I_s = amperes flowing in current-transformer secondary windings

I_e = amperes exciting current made up of components I_m and I_w. $I_e = \sqrt{I_w^2+I_m^2}$

I_m = amperes magnetizing current and equals $V/E_s = BE_s$

E_b = volts applied to external burden

Table II

I_s	E_s/N	B	G	BX	BR	GX	GR	$BR-GX$	$BX+GR$	Tan ϕ	ϕ	Cos ϕ	RCF
0.5													
1													
2													
3													
4													
5													

peres in order to cover the range for which the data may be desired because of the greater saturation at heavy fault currents.

It is likely that modifications of the curves will yield other data useful in relay and other engineering calculations. However, the purpose of the curves and data as here presented is to describe a field method that may be used primarily to determine the phase-angle errors and ratio correction factors of installed current transformers, of known turn ratio, for metering purposes. Generally this will apply to uncompensated bushing-type and wound-type current transformers, as compensation usually destroys the true turn ratio.

Appendix

Figure 3 shows a schematic drawing of a typical bushing-type current transformer. The multiratio taps are not shown. However, a well-designed multiratio current transformer will be constructed so that, for any ratio, the turns will describe at least one complete helix around the core. For this reason there is very little inducement for the flux to go any place except around the core within the helix. Since the leakage flux is extremely small the reactance component of the short-circuited impedance of the current transformer should be negligible. The actual d-c resistance of the portion of the secondary winding being considered always should be added to the burden resistance to obtain the resistance (R) used in the expressions for tan ϕ and RCF and in evaluating E_s.

In Figure 4 an equivalent circuit is shown for a current transformer. On a 1:1 turn-ratio basis, the total primary current (I_p/N) is made up of two parts, I_e, the exciting current, and I_s, the secondary current. The exciting current is dependent upon the amount of secondary voltage per turn that is required. Low secondary voltage per turn means low values of exciting current. High secondary voltage per turn means high exciting current.

The exciting current is made up of two components, I_w, the core-loss component which is in phase with E_s, and I_m, the magnetizing component, which lags E_s by 90 degrees.

The voltage induced per turn in the secondary winding and the total core losses are constant for any constant value of magnetic flux flowing around the core.

Conditions of voltage or coil turns which produce the same core flux will have definite and determinable relations existing between them.

Since the value of flux in the core is proportional to E_s/N (from the formula based on Lenz's Law, $E=4.44NF\phi$ max (10^{-8})) any change in the value of E_s attended by a proportionate change in N for a given current transformer will result in the same value of core flux and in the same total core losses. The core flux is directly proportional to the secondary-induced volts per turn, E_s/N and, for any given value of E_s/N, is also proportional to the magnetizing ampere turns, NI_m or NE_sB. Consequently, E_s/N is also proportional to E_sNB, or B is proportional to $1/N^2$.

The core losses are equal to E_sI_w or $E_s(E_sG)$. They are not necessarily proportional to E_s/N. However, for any given value of E_s/N they are constant and equal to E_s^2G. Hence, if N is made to vary, the corresponding value of E_s for the same core loss as before must vary in direct ratio to N. Therefore, under this condition it may be said that the core loss E_s^2G, is equal to K, a constant, or that G equals K/E_s^2, where E_s is proportional to N.

Thus, G equals K_1/N^2 for any given values of ϕ, E_s/N, and core loss. K_1 is a proportionality constant.

Furthermore, if the value, G_1 and B_1 are known for a current transformer of turn ratio N_1 at a given value of E_{s1}/N_1, they will be equal to these values multiplied by the ratio $(N_1/N_2)^2$ for any other ratio, such as $^1/_2$, provided E_{s2}/N_2 is equal to E_{s1}/N_1. These are the relations upon which the calculations of Figure 2 are based.

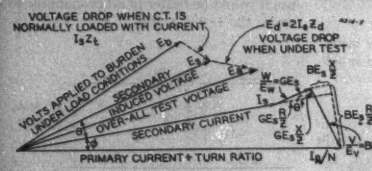
VOLTAGE DROP WHEN C.T. IS NORMALLY LOADED WITH CURRENT I_2Z_t
$E_d=2I_2Z_d$
VOLTAGE DROP WHEN UNDER TEST
VOLTS APPLIED TO BURDEN UNDER LOAD CONDITIONS
SECONDARY INDUCED VOLTAGE
OVER-ALL TEST VOLTAGE
SECONDARY CURRENT
PRIMARY CURRENT ÷ TURN RATIO

Figure 5. Vectorial representation of voltage and current values within a current transformer carrying a very heavy secondary burden

The diagram shows current and voltage vectors under load and under test conditions

Explanation of the terms used:

R, X, and Z = ohms resistance, reactance, and impedance, respectively, of the current transformer together with its total external secondary burden

$Z=\sqrt{R^2+X^2}$

ϕ = phase-angle error of current transformer in degrees

θ = characteristic phase angle of secondary burden

Tan $\theta=X/R$

E_s = volts applied to secondary circuit under test

Z_d = ohms impedance of secondary compensating burden

E_d = volts drop under test conditions across the total secondary circuit the impedance of which is equal to $2Z_d$

$E_d=2I_sZ_d$

For explanation of other items used in Figure 5 see caption for Figure 4

If it is found that the range of operation is too limited with the three-cycle log-log paper the horizontal scale may be extended to four or five cycles.

Figure 5 shows the vector relations with the exciting and core-loss components of current considerably exaggerated. It may be noted that the primary current I_p/N is vectorially equal to the sum of $I_s+GE_s+BE_s$ and algebraically equal to:

$$\frac{I_s+GE_s\left(\frac{R}{Z}\right)+BE_s\left(\frac{X}{Z}\right)}{\cos\phi}$$

where

$$Z=\sqrt{R^2+X^2}$$

The phase-angle error may be found from the tangent of the angle ϕ between I_p/N and I_s, this angle being considered positive when I_s leads I_p/N,

$$\text{Tan }\phi=\frac{BE_s(R/Z)-GE_s(X/Z)}{I_s+GE_s(R/Z)+BE_s(X/Z)}$$

$$=\frac{BRI_s-GXI_s}{(1+BX+GR)I_s}$$

$$=\frac{BR-GX}{1+BX+GR}$$

The ratio correction factor is equal to the ratio I_p/N divided by I_s. Also, $E_s/I_s=Z$. Likewise, from Figure 5 it is apparent that

$$RCF=\frac{I_s+BE_s\frac{X}{Z}+GE_s\frac{R}{Z}}{\cos\phi}$$

or:

$$\frac{I_p/N}{I_s}=\frac{\frac{I_s}{I_s}+\frac{BE_s}{I_s}\frac{X}{Z}+G\frac{E_s}{I_s}\frac{R}{Z}}{\cos\phi}$$

or the

$$RCF=\frac{1+BX+GR}{\cos\phi}$$

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D-C Arc Interruption for Aircraft

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THE present aircraft electric system uses 24 volts direct current; the future system will assuredly be of a higher voltage as aircraft and their generating systems increase in size. Whether it be direct current or alternating current depends on the relative merits of each.[1] If the new system be alternating current the problem of arc interruption is not difficult. If the new system be direct current and above 24 volts, it has been assumed that the arc-interruption problem at altitude would be quite difficult. There is, however, little quantitative data available to bear this out. An investigation was therefore initiated to obtain preliminary data on arc-interruption problems introduced by the use of higher d-c voltages.

The use of a newly developed timer for measuring the duration of arcing made it possible to obtain accurately and rapidly a large amount of quantitative data which are presented herewith.

Scope of Paper

This paper presents data on d-c arc interruption for voltages up to 250 volts at pressures from sea level to 50,000 feet altitude. Both resistive and inductive loads are investigated. The load range chosen includes small currents corresponding to relay or auxiliary-contact values, and higher currents associated with power circuits. Two general types of devices were used for the tests; namely, single- and double-break switches and a blowout-type contactor. The results are presented both in the form of maximum amperes which can be interrupted and arcing time in milliseconds. The effect of inductive loads on arc interruption is discussed briefly.

There also are presented the results of an investigation on the effect of a magnetic field on an arc, which at altitude tends to produce an arc movement in a direction opposite to that at sea level.

No attempt has been made to give theoretical or analytical explanations of the results obtained.

A parallel investigation of the voltage peaks resulting from current interruption was made at the same time and the results of this investigation are presented in a paper by Phillips and Mitchel.[2]

Conclusions

1. The interrupting ability of small gaps (of the order of 0.020 inch) increases markedly with altitude for voltages above a certain minimum (about 80 volts).

2. The interrupting ability of larger gaps (of the order of 0.220 inch) increases with altitude for voltages above a certain minimum (about 175 volts). For these larger gaps the increase is not as marked as for the smaller gap.

3. On a 30-volt system the arcing time *increases* with altitude. On a higher-voltage system (above some minimum depending on the gap) arcing time *decreases* with altitude.

4. For double-break devices handling resistance loads, the maximum volt-amperes which can be interrupted increases rapidly as voltages decrease below 100 volts.

5. The interrupting ability of a double break, each gap being 0.020 inch, on a 30-volt system is about five times that of a single 0.040-inch gap.

6. The arc-interrupting ability of a device improves with increased humidity both at sea level and at reduced pressure corresponding to 60,000 feet.

7. A blowout-type contactor of the type used in industrial work will handle the power requirements of aircraft (100 kva and above at voltages up to 250 volts direct current both at sea level and altitude. Special attention must be paid in the design to ensure successful operation with low currents at altitude.

8. A reverse blowout effect exists at altitude which tends to move a low-current arc under the influence of a magnetic field in a direction opposite to that at sea level. This effect was not observed at currents above 50 amperes. The reverse forces apparently are quite small.

9. There is an effect observable with small gaps on direct current, similar to that on alternating current, whereby it is possible to increase the maximum interrupting capacity of a pair of contacts by *decreasing* the gap.

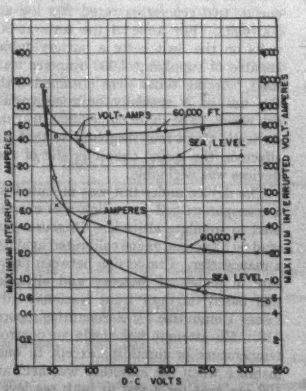

Figure 1. Comparison of the interrupting ability versus voltage at sea level and 60,000 feet altitude for the double-break Switchette on resistive load

Gap: 0.020 inch per break

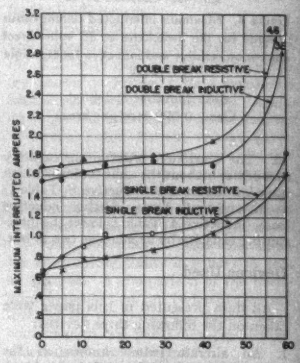

Figure 2. Maximum interrupted current versus altitude for the double-break Switchette at 125 volts direct current on resistive and inductive loads, both single and double break

Load: Inductive *B*, Table I
Gap: 0.020 inch per break

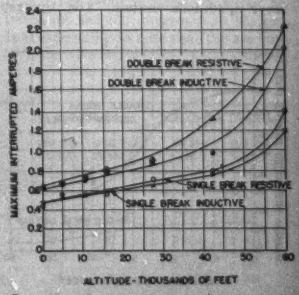

Figure 3. Maximum interrupted current versus altitude for the double-break Switchette at 250 volts direct current on resistive and inductive loads, both single and double break

Load: Inductive *B*, Table I
Gap: 0.020 inch per break

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The authors acknowledge the assistance of J. P. Kone who was responsible for a large part of the data on the Switchette.

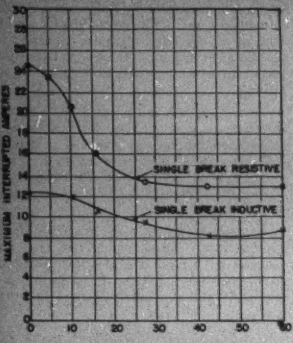

Figure 4. Maximum interrupted current versus altitude for the Switchette at 30 volts direct current on resistive and inductive loads, single break

Load: Inductive *B*, Table I
Gap: 0.020 inch per break

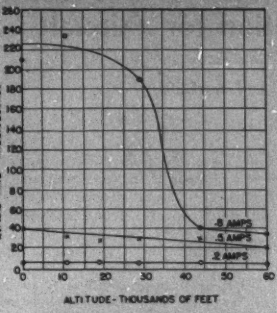

Figure 6a. Average arc time versus altitude for the double-break Switchette at 125 volts direct current on inductive load

Each point represents the average of ten readings of arc time
Load: Inductive *A*, Table I, 0.2 ampere—two coils in series. Parallel combinations of these for higher currents
Gap: 0.020 inch per break

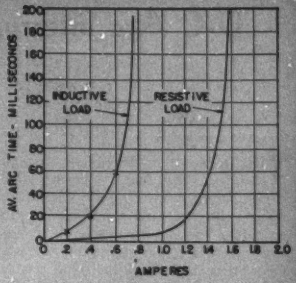

Figure 6b. Average arc time (ten readings) versus current for the double-break Switchette at 125 volts on both resistive and inductive loads at sea level

Load: Inductive *A*, Table I, 0.2 ampere—two coils in series. Parallel combinations of these for higher currents
Gap: 0.020 inch per break

10. The maximum interrupting capacity of a device is about the same for loads which have low inductance (inductive *B*, Table I) as for resistance loads. Highly inductive loads (inductive *A*, Table I) lower the interrupting capacity by as much as two to one.

Devices Used

All data presented in this paper were taken on the following three devices:

1. An aircraft switch known as the Switchette. This is a small double-break switch rated at ten amperes, 30 volts, single circuit, inductive load, at all altitudes. It has silver tips of one-eighth-inch diameter and a gap of 0.020 inch. It requires from one to two milliseconds for the tips to travel across the 0.020-inch gap.

2. A double-break switch with a bridge-type movable contact arm carrying silver tips about one-half inch in diameter on seven-eighth-inch centers. The tip gap was set at 0.220 and 0.312 inch. This unit was part of a commercial size 1 contactor having a tip rating on alternating current of 25 amperes and a motor rating of 7½ horsepower at 550 volts. The opening speed is about 20 inches per second.

3. An industrial blowout-type contactor with copper tips rated at 100 amperes, 600 volts, direct current. The gap length on this device is $^{19}/_{32}$ inch and there are 11 turns in the blowout field. In this device the arc transfers from the tips to stationary arcing horns so that the opening speed does not usually affect arc interruption.

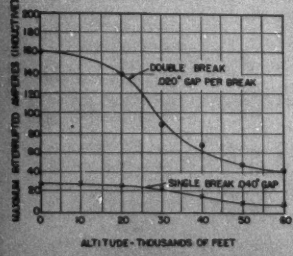

Figure 5. Comparison of maximum interrupted current versus altitude for the 0.040-inch-gap single-break Switchette and the 0.020-inch-per-break double-break Switchette on inductive load at 30 volts direct current

Load: Inductive *B*, Table I

Method of Test

Power for most tests was supplied by one or two generators rated 200 kw at 300 volts. For some of the tests at 30 volts on the Switchette a battery table capable of supplying 2,000 amperes was used. Arcing times were obtained with the use of a specially built electronic arc timer. The input impedance to this device is about four megohms so that its effect on the arcing characteristic of the devices was negligible.

The device under test was mounted in a transparent bell jar which was evacuated to simulate altitude. Pressure was read on a vacuum gauge calibrated against a manometer. Conversion between pressure in inches of mercury and altitude was based on data from National Advisory Committee for Aeronautics report 218. No attempt was made to control temperature or humidity except in one instance when the humidity was held at 100 per cent for a test at both sea level and altitude. The device was operated at 20 make and breaks per minute for the lower currents (100 amperes and below) and about five to ten operations per minute at the higher currents. In all cases sufficient on-time was allowed for the current to reach its steady state value before breaking the circuit. Ten readings were taken at each set of conditions when obtaining arc-time data so that each point on the presented curves is the average of ten readings. To obtain the data showing the maximum current which a device could handle, the current was increased in small steps taking ten interruptions at each point, until the current was found at which the arc would not extinguish.

Loads—Inductive

The loads used in these tests are those designated in Table I. The inductance

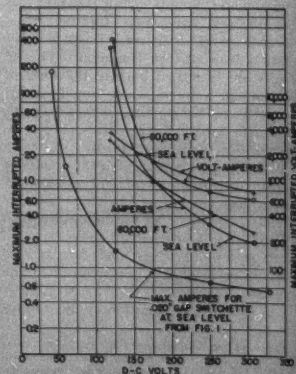

Figure 7. Comparison of the interrupting ability versus voltage at sea level and at 60,000 feet for the 0.220-inch-gap-per-break double-break contactor on resistive load

One curve for the Switchette from Figure 1 is shown for comparative purposes

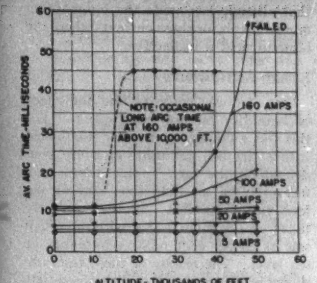

Figure 8a. Average arc time versus altitude for the double-break contactor at 60 volts direct current on inductive load

Each point represents the average of ten readings of arc time
Load: Inductive C, Table I
Gap: 0.220 inch per break

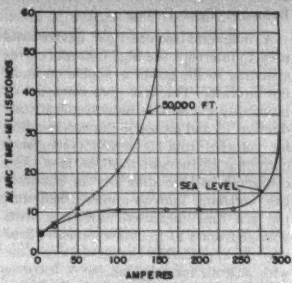

Figure 8b. Comparison of average arc time (ten readings) versus current at sea level and 50,000 feet for the double-break contactor on inductive load at 60 volts direct current

Load: Inductive C, Table I
Gap: 0.220 inch per break

given is that defined as differential inductance.[3] This inductance is obtained from a step-by-step solution of the oscillogram of current rise under constant voltage using the equation $Ldi/dt + Ri = E$. Although the values of inductance are given only at 50 per cent and 100 per cent current, a continuous curve of inductance versus current can be obtained from the oscillogram.

Discussion of Data

Table II shows the average arc time on a 30-volt system for several commercially available aircraft devices. It is presented here merely to give some factual data and establish the order of magnitude of the arcing times which are now obtained.

Switchette, 0.020-Inch Gap

Figures 1 through 6 inclusive present results obtained with the Switchette. Figure 1 is a plot of maximum interrupted amperes and maximum volt-amperes versus voltages at sea level and 60,000 feet for resistance load. The rather surprising result should be noted that for voltages above 80 volts interruption *improves* with altitude. The complete curves of maximum amperes versus altitude for 125 volts direct current and 250 volts direct current which were taken for an inductive and a resistive load, both single and double break, are given in Figures 2 and 3. Again it will be noted that interrupting capacity increases with altitude.

Figure 4 compares interruption for resistive and inductive loads versus altitude at 30 volts direct current. Figure 5 shows a comparison of the interrupting ability on inductive load of a double break of 0.020 inch per break with one single break of 0.040-inch gap. The large interrupting ability of the double break at 30 volts is probably due to the fact that the minimum voltage required to maintain an arc in air is approximately 15 volts per break.

Figure 6a shows arcing time versus altitude for three currents at 125 volts. The shorter arcing times at altitude lead to the conclusion that interruption improves with altitude at this voltage, which is in agreement with data shown in Figure 1. Figure 6b shows average arc time versus amperes at 125 volts at sea level for a resistance load and a very highly inductive load. The very sudden change in arc time as the switch approaches its limit is clearly shown. The difference in maximum interrupting ability between this curve and that of Figure 2 is due to the difference in load inductance.

Double Break, 0.220-Inch Gap and 0.312-Inch Gap

Data were taken on a conventional double-break switch for gaps of 0.220 inch and 0.312 inch. Only the data taken at 125 volts are submitted for both gaps; the majority of the results shown are for the 0.220-inch gap.

The maximum current and maximum volt-amperes interrupted versus voltage for 0.220-inch-gap double-break switch are shown on Figure 7 for a resistance load at sea level and 60,000 feet. Again an improved interruption at the higher voltages is noted, but the voltage above which arc interruption improves is approximately 175 volts for this gap. There is only a slight increase in the current which can be interrupted at altitude compared to sea level for voltages above 175 volts; for voltages below this value the interrupting ability is noticeably less at altitude. A comparison of the maximum currents that can be handled at sea level by the 0.220-inch-gap double-break contactor and the 0.020-inch-gap Switchette is also shown in Figure 7.

The double-break switch, when operated on 30 volts direct current, interrupted currents of 1,000 amperes, both resistive and inductive, without difficulty at both sea level and 50,000 feet. No curve has therefore been plotted for this voltage.

Figures 8a and b show the operation of this device at 60 volts with varying altitude. The point of failure occurred between 100 and 160 amperes at 50,000 feet. It is interesting to note that the arc time

Table I. Load Inductance

Load Designation	Load	Load Data	Load Rating 100 Per Cent V	Load Rating 100 Per Cent I	Inductance, Henries a 50 Per Cent I	Inductance, Henries a 100 Per Cent I
Inductive *A*	Series and series-parallel combinations of d-c industrial relays; data given for each relay	9,600 turns, 1.5-square-inch iron area, armature sealed	125	0.42	55	8
Inductive *B*	Parallel combinations of d-c industrial relays; data given for each relay	715 turns, 0.6-square-inch iron area, armature sealed	8	2.6	0.10	0.08
Inductive *C*	D-c series-motor field *MDO*-109, 150 horsepower	Series field and commutating field	220	480	0.002	0.0044
Inductive *D*	D-c series-motor field *MDO*-105	Series field	220	120	0.010	0.018
Inductive *E*	D-c series-motor fields *MDO*-105 and 106 in series	Series fields	220		0.012	0.034
Inductive *F*	Aircraft series motor, 1/18 horsepower	Armature and field in series—rotor blocked	24	17.3	0.0033	0.002
Inductive *G*	Aircraft series motor, one-eighth horsepower	Armature and field in series—rotor blocked	24	31.7	0.003	0.003
Inductive *H*	100-ampere-dynamotor contactor coil	2,300 turns, 0.5-square-inch iron area, armature sealed	28	0.54	2.4	1.5
Inductive *J*	Solenoid-type 200-ampere contactor coil		24	0.42	4.2	1.0
Inductive *K*	Balanced-armature-type 100-ampere contactor coil	3,100 turns, 0.09-square-inch iron area, armature sealed	24	0.19		
Inductive *L*	Four-horsepower aircraft-motor field	Shunt field	24	9.6	0.06	0.03

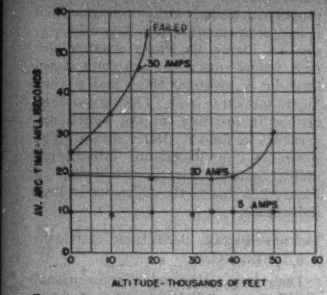

Figure 9a. Average arc time versus altitude for the double-break contactor at 125 volts direct current on inductive load

Each point represents the average of ten readings of arc time
Load: Inductive *C*, Table I
Gap: 0.220 inch per break

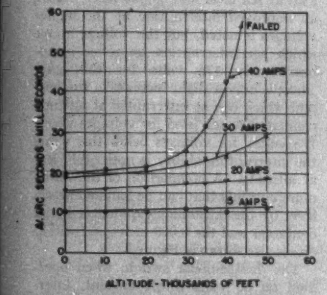

Figure 9b. Average arc time (ten readings) versus altitude for the double-break contactor at 125 volts direct current on inductive load

Load: Inductive *C*, Table I
Gap: 0.312 inch per break

gave an indication of impending failure at 160 amperes by an occasional reading of long arc time before the altitude was reached at which failure finally occurred.

Figure 9a shows the performance of the 0.220-inch-gap switch while Figure 9b shows the performance of the 0.312 inch gap, both on an inductive load at 125 volts. The increased gap has the larger interrupting ability both at sea level and altitude.

Figures 10a and b are taken at the same voltage as Figure 9, the only difference being a higher inductance load. The point of failure has dropped somewhat lower, and the arcing times are longer at the higher amperes.

On 250 volts direct current this device will interrupt only three or four amperes inductive load. It should be noted from curves 7, 8, and 9 that interruption at altitude does not improve for this gap.

Blowout-Type Device

A magnetic-blowout-type device was used to interrupt the high currents corresponding to the power available on modern aircraft. The first tests consisted of interrupting a 40-kva inductive load (inductive *C*) and measuring the arcing time for voltages from 30 to 250 volts direct current at altitudes up to 50,000 feet. The contactor had no difficulty in handling this constant kilovolt-ampere load and the arc time increased uniformly with voltage from 8 to 15 milliseconds. Three was no appreciable change in arc time with altitude for this load.

Figures 11a, 12a, and 13a show the operation of the blowout-type contactor at 60 volts, 125 volts, and 250 volts in arcing time versus altitude. Figures 11b, 12b, and 13b show arcing time at sea level and 50,000 feet versus amperes. It will be noted that a series blowout-type contactor at altitude has an arc-time characteristic very similar to its characteristic at sea level. This means that the device can successfully handle currents from its rating to ten or more times its rating with essentially constant arc time. A blowout-type contactor inherently has a weak point characterized by long arc times at currents around 20 per cent of its rating. This is the range in which the blowout field, because of the low current, is too weak to be effective and the contactor depends primarily on its large gap to break the current. It will be noted that this contactor, although operating successfully at sea level, failed on 250 volts in the low-current range, indicating that altitude has made the interruption more difficult for those currents where the blowout field is ineffective.

Table II. Comparison of Arcing Times at 30 Volts Direct Current

Load: Inductive *C*, Table I

Device	Gap Break, Inch	Current, Amperes	Average Arc Time (Ten Readings) Milliseconds at Sea Level	Milliseconds at 50,000 Feet
Switchette	0.020	5	5	5
		10	5	5
		50	12	23
Double-break contactor (referred to in paper—devices used)	0.312	5	4	4
		10	4	4
		20	5	5
		50	7.0	7.5
		112	9.5	12.5
		220	7.0	17
Double-break aircraft contactor rated 50 amperes	0.0625	5	5.5	6
		10	6	6
		20	6.5	7
		30	7	7.5
		50	9	10
		100	19.5	24
		150	25	33.5
Double-break aircraft contactor rated 100 amperes	0.125	150	16	22
Double-break aircraft contactor rated 200 amperes	0.125	150	12.5	18.5

Effect of Humidity

One test was made to find the effect of humidity on arc interruption. For this test a container of water was boiled within the bell jar until moisture condensed on the jar. Arcing times were measured on an inductive load at sea level and 60,000 feet. Similar data were taken on the same device with air which was at 20 per cent relative humidity at sea level. The results of these tests are shown in Figure 14. It will be noted that there is some improvement in arc interruption due to increased humidity.

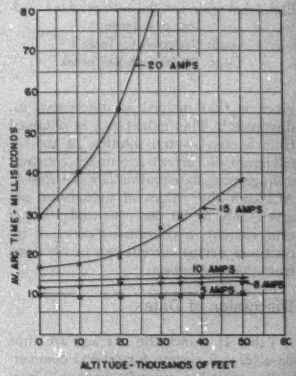

Figure 10a. Average arc time versus altitude for the double-break contactor at 125 volts direct current on inductive load

Each point represents the average of ten readings of arc time
Load: Inductive *E*, Table I
Gap: 0.220 inch per break

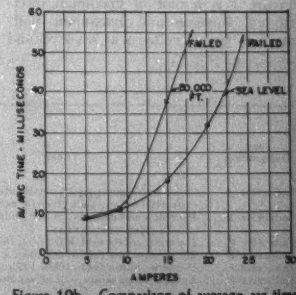

Figure 10b. Comparison of average arc time (ten readings) versus current at sea level and 50,000 feet for the double-break contactor on inductive load at 125 volts direct current

Load: Inductive *C*, Table I
Gap: 0.220 inch per break

Reverse Blowout at Altitude

It has been known for some time that at altitude an arc may move under the influence of a magnetic field, in a direction opposite to that in which it moves at sea level. To investigate this effect two devices were used. The first had as electrodes a pair of slightly bowed copper bars mounted to make contact at their center. They were arranged so that the arc could move horizontally, equally well in either direction. A separately excited source supplied blowout-field excitation.

Using only 125-volt d-c supply, arc currents from three to seven amperes, both inductive and resistance loads, and gaps of one-eighth inch, one-fourth inch, three-eighths inch, and one-half inch, it was found that as pressure was reduced the arc moved slower and slower in the normal direction until finally it did not move. The altitude at which this occurred is shown in the following table:

Gap, Inch	Current, Amperes	Direct Voltage	Altitude, Feet
1/8	5	125	38,000
1/4	5	125	46,000
3/8	5	125	47,000
1/2	5	125	56,000

For altitudes above those shown the arc was driven in the reverse direction.

It will be noted that as the gap increased the altitude required to stop all movement in the normal direction also increased. Changing the field strength over a wide range did not appear to affect this phenomenon.

The second device used consisted of a double-break switch with two permanent-magnet blowouts and electrodes so arranged that each arc could travel in either of two directions. Using this device with a gap of 1/16 inch and 3/32 inch it was observed that the reverse blowout effect did not take place on both gaps, one reversing at altitude and the other merely decreasing in velocity. Investigation revealed that there was a dependence on the direction of current flow. If the cathode was in a strong magnetic field near the magnet the reverse blowout occurred but when the cathode was in a weaker field reversal did not occur.

As the pressure in the vacuum chamber is lowered the arc is observed to move slower and slower. It finally stops moving and then if conditions are right moves in the opposite direction. At this point it is a diffuse discharge, its cross section having increased many times. It is easily observable that the different parts of the arc are acted on by opposing forces, for the arc column will sometimes travel in one direction while the cathode spot moves in another. It appears that the reverse blowout forces act primarily on the region near the cathode spots while the magnetic field as usual acts on the arc column. At very small gaps these same phenomena can sometimes be observed at sea level.

In general, the reverse force appears to be quite small and it may be overcome simply by convection. The reverse arc movement has been reported and discussed in a paper by C. G. Smith.[4]

General Discussion

Inductive Loads

There is no standard method of defining the type of load to be used for interruption tests. Often a load is designated merely as "inductive," the inference being that such an inductive load is typical or similar to those which the device must handle. In some cases a time constant for the circuit is specified as in the Navy Aeronautical Specification for contactors *M*569. This is an inadequate designation for it is possible to make up any number of d-c circuits which have the same time constant but whose severity of interruption can be many times different. If an additional specification is made regarding the current at which a certain degree of saturation exists, then a time-constant definition of a circuit is more nearly adequate. Another method of specifying load is to give the dimensions and turns of the test reactor or device. Here again attention must be paid to saturation. The standard test inductors specified by the Bureau of Aeronautics, Navy Department, *E*180, saturate at about 20 per cent of their rated current. This reactor will then have appreciable inductance up to 20 per cent of its rating and negligible inductance thereafter. A more fundamental method of defining the inductance of a circuit for interruption comparisons would be to give the total stored magnetic energy in the circuit. However, this is hard to measure, whereas a curve of inductance versus current can be obtained simply for any combination of devices from the current–time curve.

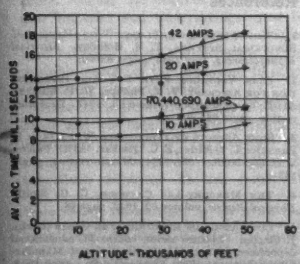

Figure 11a. Average arc time versus altitude for the 0.590-inch-gap blowout-type contactor at 60 volts direct current on inductive load

Each point represents the average of ten readings of arc time
Load: Inductive C, Table I

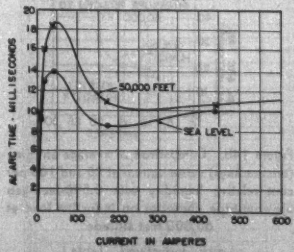

Figure 11b. Comparison of average arc time (ten readings) versus current at sea level and 50,000 feet at 60 volts direct current for the 0.590-inch-gap blowout-type contactor on inductive load

Load: Inductive C, Table I

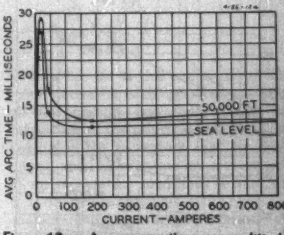

Figure 12a. Average arc time versus altitude for the 0.590-inch-gap blowout-type contactor at 125 volts direct current on inductive load

Each point represents the average of ten readings of arc time
Load: Inductive C, Table I

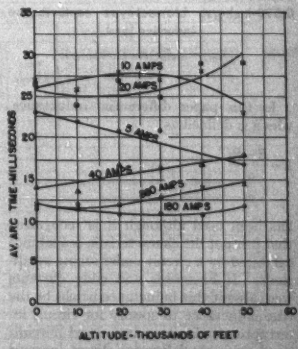

Figure 12b. Comparison of average arc time (ten readings) versus current at sea level and 50,000 feet at 125 volts direct current for the 0.590-inch-gap blowout-type contactor on inductive load

Load: Inductive C, Table I

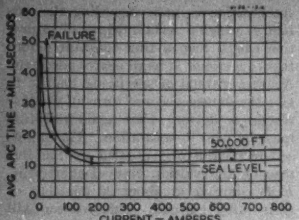

Figure 13a. Average arc time versus altitude for the 0.590-inch-gap blowout-type contactor at 250 volts direct current on inductive load

Each point represents the average of ten readings of arc time
Load: Inductive C, Table I

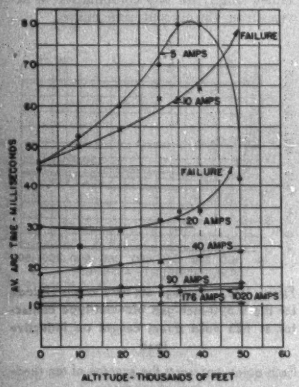

Figure 13b. Comparison of average arc time (ten readings) versus current at sea level and 50,000 feet at 250 volts direct current for the 0.590-inch-gap blowout-type contacto on inductive load

Load: Inductive C, Table I

In this paper differential inductance, which is defined as

$$L = \frac{E - Ri}{\frac{di}{dt}}$$

has been used although it is recognized that it is not the characteristic inductance exhibited by a circuit under arcing conditions. If hysteresis and eddy currents were absent this inductance would be the true inductance to specify for circuit interruption. In any iron-cored circuit, however, especially on direct current where solid iron is used, these core-loss effects are present and so the true inductance which affects arc interruption will vary considerably depending on the current and the speed with which the current is interrupted. The differential inductance is used in this paper because it is readily obtained and is an indication of the inductance of a device.

Arc Time

It should be noted that the curves present interruption data in two forms—actual arc time in milliseconds and maximum interrupting ability. The latter is often the criterion used to establish the interruption rating of a device, the actual rating being a certain percentage of the maximum current which can be broken. This method of evaluating interrupting ability presupposes a short arc time at rated current and for sea-level tests this is usually correct. However, when investigations of interruptions at various pressures are made, it is advantageous to discover by means of actual arc times the point at which erratic performance begins.

Furthermore, arcing time is a good quantitative measure of the comparative performance of devices. In most cases a sudden increase in arcing time anticipates actual failure of the device. Arc time is also important for evaluating tip life.

For small direct currents where high-voltage surges are usually initiated by the arc interruption, the use of a magnetic oscillograph of the usual sensitivity may lead to erroneous values of arcing time and arcing characteristics.

Small-Gap Effect

The fact that a small gap of the order of one millimeter may have a higher interrupting ability than a larger gap is a well known phenomenon in a-c[5] arc interruption. Investigation of d-c interruption at small gaps has shown that a similar effect exists for direct current. Tests have shown that it is often possible to interrupt more current at either 125 volts or 250 volts, inductive or resistive load, with gaps about 0.005 inch or 0.010 inch than with gaps of 0.030 inch, especially at the higher altitudes. Practical considerations such as metal transfer or the building up of beads on tips due to arcing tend to limit the practical usefulness of this observed phenomenon.

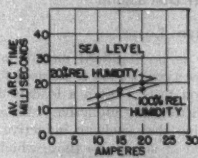

Figure 14a. Comparison of average arc time versus current at 20 and 100 per cent relative humidity with 0.590-inch-gap blowout-type contactor on inductive load at sea level

Each point represents the average of ten readings of arc time
Load: Inductive C, Table I

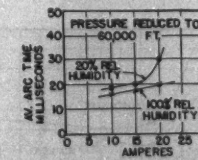

Figure 14b. Comparison of average arc time (ten readings) versus current at 20 and 100 per cent relative humidity with 0.590-inch-gap blowout-type contactor on inductive load at 60,000 feet altitude

Load: Inductive C, Table I

Summary

This paper has presented quantitative information obtained on various direct voltages. It should be cautioned that the maximum interrupted currents given here should not be taken as the rating of a device. The actual rating is a certain fraction of the maximum and is dependent on factors such as factor of safety desired, tip life expectancy, maximum arcing time allowable, and so forth.

Based on data obtained so far, the arc-interruption problem at higher direct voltages appears quite feasible. Possible system voltages are three wire, 250 volt, or even 600 volt as far as arc interruption is concerned.

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Basic Considerations in the Selection of Generators and Batteries for Aircraft

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ELECTRIC systems as used on aircraft have developed from a more or less accessory status in older types of aircraft to a place of prominence in modern types of such importance that safety of operation is often dependent to a limited extent on electric-system reliability. Because of its importance the general requirements of the electric system must be conceived for a proposed new airplane design when the design is in an embryonic state. Preliminary electric-load requirements must be calculated and, as design changes are made, must be revised repeatedly in order to co-ordinate properly the electric-system design with the other design characteristics of the airplane.

During this process of development all controlling design features of the complete electric system should be considered under operating conditions approximating, as closely as possible, those which would be obtained during actual operation.

To facilitate the calculation of electric loads of an airplane in any design stage, and with accuracy consistent with good design, the method described in this paper has evolved from a study of this problem extending over a period of several years.

Method of Analyzing Aircraft Loads

To select a generating source adequate to meet the electric-load requirements of an airplane under applicable operating conditions requires a systematic survey of those conditions with the most severe load combinations that may be encountered. Thus, the number of generators and batteries and their ratings must be determined from the proposed system load calculations with due regard to the variable nature of the loads and to other influencing characteristics.

Since the preliminary studies of electric loads and the determination of required generating capacity for a proposed airplane present the greatest obstacles, the procedure discussed in this paper attempts to clarify this initial phase of design by considering the several factors contributing to the selection of generators and batteries; however, the method used for calculating loads is equally applicable to all stages of design with no variations nor exceptions.

The method of calculation as presented in this paper is founded on the fact that the established standard for rating electric machinery is based on internal heating of the machine; that is, the maximum output of the machine is limited by the maximum safe operating temperature for the type of insulation used. This applies to aircraft generators where the temperature rise of the generator is a function of its internal losses, the most important of which are windage, friction, hysteresis, eddy-current and copper losses. Of these, windage, friction, hysteresis and eddy-current losses are functions of generator speed and field excitation. Copper losses are the products of the resistances of field and armature and the squares of their respective currents, and usually may be considered the principal source of heating when the generator is operated at 50 per cent rating or above. This is particularly true of present-day main engine generators which are cooled by air blast, since an increase in windage, friction, hysteresis and eddy-current losses due to higher generator speed is compensated by the increased blast resulting from the greater forward airplane speed which usually accompanies an increase in engine speed. Hence, by assuming that all, instead of only the major part, of the losses vary as the square of the armature current, this method of evaluating variable loads is slightly conservative.

The energy which produces heating of the generator conductors in any given period of time, T, is proportional to the integrated squares of instantaneous values of current as shown in the following equation:

$$W = R \int_{T_1}^{T_2} i^2 dt \text{ watt minutes}$$

where $T = T_2 - T_1$.

The steady value of current that would produce the same heating is equal to the square root of the mean square of the instantaneous currents integrated over the period T.

$$I_{rms} = \sqrt{\frac{W}{RT}} = \sqrt{\frac{1}{T} \int_{T_1}^{T_2} i^2 dt}$$

With the aid of this equation the load requirements for each operating condition of the airplane, and consequently the magnitude of the principal factor causing heating of the generators, may be determined, and it is of prime importance that all main operating conditions be analyzed to preclude the omission of any operating characteristics that might influence the generator capacity. The number of different operating conditions for a comprehensive analysis is dependent on the type of aircraft—land based or sea based—

Figure 1. Sample of chart used for tabulating aircraft electric loads

MODEL ____ ELECTRICAL POWER ANALYSIS CHART

____VOLT D.C. SYSTEM

NO.	ITEM	OPER. LOAD PER UNIT WATTS	OPER. LOAD PER UNIT AMPS.	TOTAL NO. OF UNITS	UNITS OPER. SIMULT.	SECONDS PER OPER.	TOTAL OPER. / DAY / HOUR	PART NUMBER	OPERATING CONDITIONS: START COL. 1 AMPS. 10 MIN.	STAND-BY COL. 2 AMPS. 20 MIN.	TAKE-OFF COL. 3 AMPS. 10 MIN.	LAND COL. 4 AMPS. 10 MIN.	CRUISE COL. 5 AMPS. 1 HOUR	NOTES
1														1
2														2
3														3
4														4
5														5
85														6
86														7
87														8
88														9
89														10
90														11
91														12
92														13
93														14
94														15
95														16
96														96
97														97
98														98
99														99
100														100
	TOTALS													
T1	MAXIMUM DEMAND (SIMULTANEOUS OPERATION- ALL APPLICABLE LOADS)													T1
T2	SHORT TIME PEAK CURRENT (R.M.S. FOR 2 MINUTES)													T2
T3	R.M.S. VALUE OF CURRENT (FOR REMAINDER OF PERIOD)													T3
T4	SHORT TIME PEAK PER GENERATOR - NORMAL OPERATION													T4
T5	R.M.S. CURRENT PER GENERATOR - NORMAL OPERATION													T5
T6	SHORT TIME PEAK PER GENERATOR - EMERGENCY OPERATION													T6
T7	R.M.S. CURRENT PER GENERATOR - EMERGENCY OPERATION													T7

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and on the use of the aircraft—military or commercial. Operating conditions may include loading, standby, starting, take-off, cruise, combat, landing, and others as may be applicable.

The first step in making the analysis consists of listing each item of utilization equipment on a chart similar to that shown in Figure 1. Adjacent to each item and in columns provided for the purpose are listed amperes per unit, total number of units, units operating simultaneously, seconds per operation, and total operations per unit per hour. Following this, the applicable operating conditions are

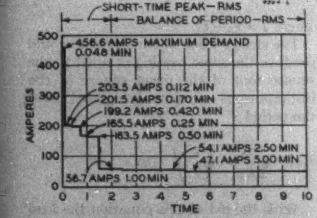

Figure 2. Block diagram illustrating the sequence of loads as used for calculating rms values of current

set up in columns, and the current for each item operating under each of the several conditions is noted.

Individual loads under each operating condition may be classified as continuous loads, which exist for the duration of the operating period considered, and noncontinuous loads, which exist for various portions of the operating period. Examples of these classifications are heating equipment, ventilating equipment, radio receivers, and inverters which are usually operated continuously, while items such as control-surface equipment, landing-gear retraction equipment, and engine starters are operated noncontinuously.

Calculations of maximum demand, short-time peak, and rms values of current for each of the several operating conditions with proper consideration of other influencing factors provide sufficient data to determine the number and capacity of generators and batteries for a given installation.

As indicated in Figure 2 and Table I, it is assumed in this method of calculation that for each operating condition all applicable loads begin simultaneously at the start of the period. This assumption serves to simplify calculations and its justification lies in the impracticability of attempting to estimate the actual order of occurrence of the various loads. This arbitrary sequence leads to pessimistic values of maximum demand and rms current but serves to compensate for neglecting motor-starting inrush currents. In addition to heating, the maximum demand must be considered because of the effect of high momentary currents upon commutation, regulation, and instantaneous torque demand on the generator drive.

Because of the relatively small margins of safety possible in aircraft generator design,[1] it is of great importance that adherence to design ratings be exercised. Many main engine d-c generators have a continuous full-load rating, a two-minute 50 per cent overload rating, and a five-second 100 per cent overload rating, whereas, most auxiliary power-plant generators have a continuous full-load rating and a five-minute 50 per cent overload rating. Thus, it is necessary when analyzing the operating conditions to evaluate the overloads for which there is a possibility of occurrence. This gives rise to the short-time peak current which is the rms value calculated over a two- or five-minute period, whichever is applicable.

The rms value computed for the balance of the period, after the short time peak has been found, is somewhat pessimistic as a basis for determining the continuous-duty capacity[2] of the generator

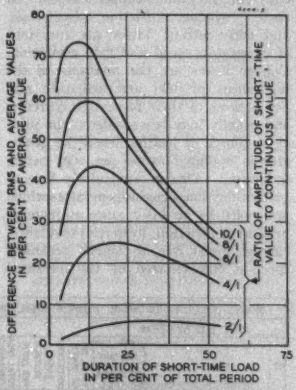
DIFFERENCE BETWEEN RMS AND AVERAGE VALUES IN PER CENT OF AVERAGE VALUE
RATIO OF AMPLITUDE OF SHORT-TIME VALUE TO CONTINUOUS VALUE
10/1
8/1
6/1
4/1
2/1
DURATION OF SHORT-TIME LOAD IN PER CENT OF TOTAL PERIOD

Figure 3. Curves showing percentage difference between rms and average values of current

supply, since the arbitrary sequence of the various loads tends toward larger rms values; but, on the other hand, the average value for the same period is optimistic. Thus, if both rms and average values are calculated, a bracket is established which extends from the most unfavorable to the most favorable sequence; hence, the actual operation must fall somewhere between the two extremes. In the absence of large part-time loads the rms and average values will approximate each other very closely, indicating that the sequence of application of the loads for this condition is of little importance; however, if the short-time loads are large their importance becomes of more concern. The difference between the rms and average values over an operating cycle is a function of the ratio of amplitudes of the short-time current and the continuous current, and also of the duration of the short-time current in per cent of a complete operating cycle. Figure 3 presents a family of curves showing the amount that the rms value exceeds the average value when a single short-time load is considered.

Table I and Figure 2 serve to illustrate the method of calculating maximum demand, short-time peak and rms currents for a typical operating condition.

Use of Load Calculations in Selection of Generators

With the aid of the most severe service requirements of the power supply, as made available by the calculations of maximum demand, short-time peak, and rms values of current for the several operating conditions, the active generator capacity may be determined. In addition to the active power requirements, other considerations which bear on the selection of the number and rating of generators are: emergency reserve capacity, excess capacity for future system growth, current peaks carried by batteries in low-voltage d-c systems, amount of monitoring that can be tolerated if necessary, altitude rating of generators, generator operating speed, and volt-ampere characteristics of the power-supply system.

Emergency Reserve Capacity

The capacity which should be provided for reserve depends on the likelihood of the generators or their controls becoming damaged or inoperative, and also depends on the importance of reliability of electric power supply, the reliability requirements in general being a function of size and power of the airplane. For almost all types of military aircraft reliability is usually of extreme importance from the

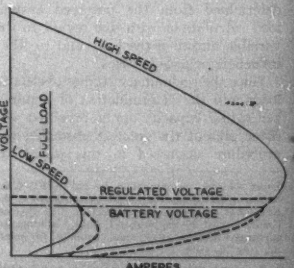

Figure 4. Aircraft-electric-system volt-ampere characteristics

—— Generator volt-ampere characteristic
---- System volt-ampere characteristic

standpoints of protection and safety of flight. For large commercial aircraft and especially those for which flight safety is dependent on electrically operated equipment, such as control surfaces, assurance of uninterrupted service is equally important, whereas, for small low-powered aircraft the loss of a generator normally would be of small consequence. Thus, the reserve capacity needed to insure reliability of electric power may vary from 0 to 100 per cent and is purely an arbitrary figure depending on the function of the airplane, flight safety requirements, and the probability of damage to the system.

Reserve capacity is normally provided in the form of more or larger generators, since the weight of batteries to supply power for an extended time is usually prohibitive. However, a complete evaluation of all factors sometimes will dictate the omission of part or all of the normal reserve generator capacity, and in such cases any generator failure will make it imperative to monitor the demand for power by limiting the operation of the utilization equipment. In case all the generator capacity is lost, failure to monitor will result in rapid discharge of the batteries with consequent loss of radio contact, electrically operated engine instruments, and possibly propeller pitch control. In case only part of the generating capacity is lost, the remaining units probably will be operating under an overload. In many ships not having a flight engineer, overload on the generator(s) is very likely to escape attention until the remaining units have overheated and failed. The importance of monitoring before this condition occurs is readily apparent and has led to serious consideration of the desirability of providing a warning whenever serious generator overheating has occurred. The addition of a built-in thermostat in every generator would provide a simple means of operating a red warning light.

Capacity Allowed for System Growth

The amount of capacity provided for future system growth is greatest in the initial stages of the system design, since, as the development of the airplane progresses, the initial allowance probably will be used. It has been common practice to provide from 10 to 25 per cent over and above the initial calculated requirements, depending on the conservatism of the design.

Current Peaks

The maximum demand current for any operating condition is often of a momentary nature which may be within the generator five-second rating previously mentioned. However, in the event that the maximum demand exceeds this rating in either amplitude or time, it is often desirable and advantageous to permit the batteries to supply the additional load on low-voltage systems. This is accomplished by co-ordinating properly the generator-voltage regulator combination to obtain a drooping voltage characteristic, as overload increases, of such nature as to reduce the generator voltage slightly below battery voltage at a predetermined overload. Any momentary current peaks are usually of such short duration that no provisions for added battery capacity are required, although this may not be true if the high-current peaks occur shortly after the batteries have undergone a period of high discharge. Such a condition might occur during take-off after main-engine starting has lowered battery capacity, or during landing if the engines are operated at low speed. Under the latter operating condition batteries would be required to supply a large portion of continuous loads in addition to peaks.

Monitoring

In some instances where maximum demand or short-time peak currents indicate the necessity for exceptionally large generator or battery capacities, it is convenient and practicable to regulate the sequence of operation of manually controlled motors and other loads in order to prevent excessive currents, thus permitting the use of lower rated generators and batteries.

Generator Altitude Ratings

Most main-engine generators maintain full-rated output up to 30,000-feet altitude, above which the output is an inverse function of altitude. The output of auxiliary-power-plant generators, however, is fundamentally dependent on the output of the internal combustion engine which is essentially an inverse function of altitude from sea level. Reduced auxiliary-power-plant ratings above sea level cause them to be very inefficient for altitude operation, and unless engine supercharging is provided, these units are used commonly only for ground supply and emergency reserve in flight, at reduced rating, for main-engine generators.

Generator Speed

To obtain rated output an aircraft generator must be operating within a given speed range with adequate voltage regulation. Thus, the possibility of generator speeds below the lower limit of rated speed must be given proper consideration for those operating conditions during which reduced speeds may occur. A condition of this type may become critical during landing, especially if the approach is made in a prolonged glide from high altitude, but in general would be relatively unimportant during ground operation with the main engines running.

System Volt-Ampere Characteristics

In order to prevent an unstable condition during maximum demand or short-time peak loading from which the system will not recover to normal voltage, the system volt-ampere characteristics must be co-ordinated with operating conditions. The following discussion applies to aircraft power systems consisting of

Table I. Sample of Tabulating and Calculating Loads

Continuous Loads (Current)				Noncontinuous Loads	
				Current	Time
10.4				253.1	0.048
0.3				2.0	0.16
0.2				2.3	0.33
0.4				33.7	0.75
2.5				2.0	1.00
23.0				106.8	1.50
2.7				2.4	2.50
0.1				0.2	2.50
0.5				7.0	5.00
7.0					
47.1				409.5	
I	ΔI	t	It		I²t
456.6	253.1	0.048	21.92		10,008.7
203.5	2.0	0.112	22.79		4,637.8
201.5	2.3	0.17	34.26		6,903.4
199.2	33.7	0.42	83.66		16,665.1
165.5	2.0	0.25	41.38		6,848.4
163.5	106.8	0.50	81.75		13,360.1
56.7		0.50	28.35		1,607.4
		2.00	2 314.11		2 60,036.9
			157.0 amperes (average)		30,018.4(1/2) 173 amperes (rms)
56.7	2.6	0.50	28.35		1,607.4
54.1	7.0	2.50	135.25		7,317.0
47.1		5.00	235.50		11,092.0
		8.00	8 399.48		8 20,014.4
			49.9 amperes (average)		2,501.8(1/2) 50. amperes (rms)

generators with or without batteries which have over-all volt-ampere characteristic curves having a positive slope on the low-voltage end. At the lower end of the generator-design speed range the sytem stability is most critical, since aircraft generators usually are designed, so that the low-speed volt-ampere characteristic curve intersects the regulated voltage curve at approximately 150 per cent of normal rated current. Overload ratings of the generators apply for low-speed operation of this nature insofar as heating is concerned. At this low speed continued increases in load, in excess of the point of intersection of the two curves, result in a relatively sudden drop in the generated voltage; and further increases may reduce the voltage to a point of instability such that the generator excitation fails progressively, causing the generated voltage and load current to drop to small values. Under these conditions the generator is unable to recover voltage until the load has been removed from the system. At the upper end of the speed range the generators are capable of carrying several times normal rated current for periods of time governed almost entirely by temperature rise. However, the intersection of the high-speed volt-ampere characteristic curve and the regulated voltage curve is a limiting loading condition. Loads in excess of this value result in excitation failure and consequent simultaneous reduction of generated voltage and load current. Voltage recovery can be obtained only by removing the load from the system.

The use of batteries in parallel with low-voltage aircraft generators aids in alleviating this unstable condition by increasing the amount of load that may be carried before reaching the unstable portion of the curve. However, the use of enough battery capacity to eliminate completely the positive slope portions of the system characteristic curves is not practicable from a weight standpoint.

The general form of a volt-ampere characteristic curve of an aircraft electric system composed of generators and battery is shown in Figure 4. The effect of batteries in parallel with generators on the system characteristics is shown by the broken line. It will be noted that at low speed the addition of the battery improves the stability of the system appreciably by increasing the load over that which may be carried by generators alone as shown by the solid line.

Each of the previously noted factors must be given due consideration in selecting an economical and efficient generator supply of adequate capacity and reliability.

Selection of Batteries

An aircraft battery is an inefficient source of electric power compared with the generator, but its ability to deliver high short-time currents makes it highly desirable for aircraft application on low-voltage systems. In general, its primary purpose is for ground operations when generator power is not available, while its secondary purpose is for assisting the generators by carrying high peak currents, thereby improving the stability of low-voltage systems. Also, when operated in parallel with generators, the battery acts conveniently as a filter to reduce radio-noise interference.

Two methods for reducing the weights of battery installations have been employed successfully on certain types of airplanes. The first, applicable to land-based aircraft which operate from well-organized airports, utilizes a power supply from an external source connected into the airplane system through a built-in plug-type receptacle. In this type of installation power for engine starting and normal ground loads is supplied by the external source, and the airplane battery is only required to add stability to the system by carrying high-current peaks and to provide emergency power. It is apparent that military aircraft operating from advanced bases which are not equipped with external power facilities are not adaptable to a system of this type. The second method, applicable to medium and large airplanes either land- or sea-based, employs one or more auxiliary-engine generators which provide power for ground operations. In this type of installation the battery need only be large enough to start an auxiliary engine and provide a stabilizing influence on the system.

The following discussion on batteries is based on the assumption that neither of the aforementioned methods for augmenting ground operation power is used.

Engine Starting

Normally, the battery capacity required for a given aircraft installation is basically dependent on engine starting requirements, and as such should provide sufficient ampere-hour capacity for a limited series of starting attempts without completely discharging the battery. In order to assure adequate capacity for this purpose, several factors must be considered: the normal current demands for the size and type of engine starters used, and the effect on starter current and battery capacity of the ambient temperatures that will be encountered. Also, in applications where the battery is normally required to supply power for ground operations in addition to starting, an adequate margin should be allowed, so that engine-starting capacity will not be jeopardized.

Engine starters, although energized for relatively short periods of time, draw currents of exceptionally large magnitude, in some cases amounting to many hundred amperes, imposing severe demands on the battery. Even under the most ideal conditions obtainable, these high-discharge rates reduce the effective ampere-hour capacity of the battery. It should be noted that the discharge period of a battery is not inversely proportional to the current but approaches the inverse square of the current. For example, a fully charged 34-ampere-hour aircraft battery will discharge completely at 6.8 amperes in five hours; at 54 amperes it will take approximately 20 minutes, and at 144 amperes, five minutes, its effective capacity being 34, 18, and 12 ampere-hours, respectively. In addition to the effect of the normally large current demands of the starter on the battery capacity, the effect of low ambient temperature is twofold; first, because the viscosity of lubricants increases the load requirements to overcome friction, and, second, because the effective capacity of the battery drops with the temperature.[8]

Assistance to Genrators

Improvement of system stability, by assistance to generators in supplying high peak currents, is usually assured by the battery capacity determined from other considerations, since the peak demands which exceed generator capacity are usually of very limited duration.

Selection of Auxiliary-Power-Plant Generators

For some applications on large aircraft, where power requirements for ground operations are appreciably more than engine-starting requirements, it is found practicable to utilize auxiliary power plants in addition to main-engine generators. Because auxiliary power plants are normally inefficient at high altitudes, they are seldom used for this purpose except for special applications with supercharging facilities, although their use for medium- and low-altitude operation at reduced rating is not uncommon. The method previously discussed for determining required main-engine generator capacity is directly applicable to auxiliary-power-plant capacity with reservations regarding altitude operation as here noted.

General Applications

The method of computing aircraft electric loads, herein outlined for d-c systems, is equally applicable to a-c systems with proper consideration given to power factor and phase unbalance if on a multiphase system. It is also useful in making preliminary power studies on a wattage basis before system voltage has been established.

Although this method for determining aircraft electric loads may be applied generally to all types of aircraft, the establishment of a definite procedure for selecting the number and ratings of gen-

One Type of Rotary Magnetic Clutch and Its Associated Brake Used on Aircraft Electric Motors

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EVER since the first application of the electric motor on aircraft, attempts have been made to adapt clutches and braking devices to the motor and its power transmission system with varying degrees of success. Some current objectives are:

1. To limit overtravel of and incorporate accurate positioning in a mechanism, such as landing gears, cowl, or wing flaps of an airplane.

2. To limit the application of load to a motor until such time as the motor has come up to speed.

3. To allow quick reversing of a gear train.

4. To permit temporary disengagement of load at a predetermined torque on the motor shaft (slipping clutch).

With recent accelerated development of aircraft, weight has become a major factor influencing the design of all accessories of such craft. Consequently, the lightweight high-torque high-speed electric motors developed for airplanes have challenged anew the ability of clutch and brake designers.

It is not proposed in this paper to discuss all of the numerous types of nor applications for brakes and clutches, but to consider only one type of clutch and a brake used in conjunction with it. The brake, a design of which is carried out later in this paper, is used to hold a load, through the associated power transmission system after the motor power has been cut off. Another type applies to a mechanism that may be operated manually during an emergency. This necessitates a mechanism which has a free driven disk member.

The clutch considered employs an application of the d-c short-stroke clapper electromagnet. Figure 1A shows the driven disk of the clutch which is made from one solid piece of steel and has the motor-drive pinion cut on its extremity. It is free to move axially through its bearings. Figure 1B is a view of the driving disk. This disk is keyed to the armature shaft (Figure 2) and rotates with it. The stationary clutch coil is wound around a core which forms a part of the inner housing of the driving disk. Figure 2 illustrates a section of the assembled clutch and brake with dimensions indicated. Dotted lines trace the paths of flux. This clutch has been used on a 100-watt 9,000-rpm intermittent-duty motor, developing 0.6- to 1.0-inch-pound torque. It will be noted from reference to Figure 1A or Figure 2 that there is a ring of nonmagnetic material dividing the face of the driving disk into two equal areas. The purpose of this ring is to direct the flux into the driven disk instead of allowing it to shunt across the face of the driving disk. Braking is accomplished mechanically by forcing the brake face of the driven disk (face opposite the clutch engaging one) against a ring of braking material fastened to the housing.

Different materials, including metals, have been used for both braking and slipping clutches. The slipping clutch has met with only fair success on high-speed applications. This, in no small part, is due to a changing coefficient of friction, which is in turn some function of the number of slippages. Steel upon steel has an initial coefficient of friction varying from 0.15 to 0.25. Positive engagement of the clutch allows no slippage; consequently, most clutch coils are in series with the armature. From a standpoint of economy, reliability, and ease of installation, material having a coefficient of friction from 0.2 to 0.4 is the most suitable for braking. Obviously, with the clutch and brake combination just the low-inertia driven disk is braked,

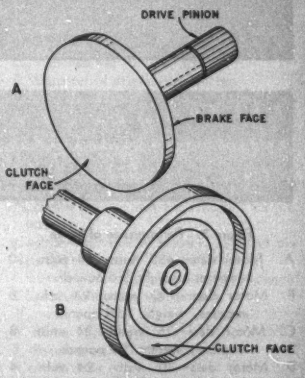

Figure 1. Rotating parts of clutch

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The authors acknowledge the aid of their colleagues of the engineering department of Lear, Inc., in the preparation of this paper.

Table 1. Absolute Permeabilities for Varying Cross Section

Location	l	A	B	Nl/In	μ
l_1	0.0	0.143	.84	10.1	8.280
l_2	0.1	0.164	.73	8.1	9.060
l_3	0.2	0.185	.65	6.5	10.000
l_4	0.3	0.212	.57	5.4	10.500
l_4	0.411	0.230	.52	5.1	10.200

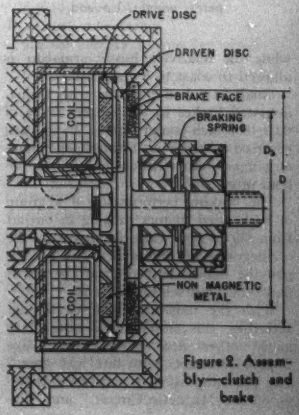

Figure 2. Assembly—clutch and brake

erators and batteries is prohibited by the variable nature of the other influencing factors.

Conclusions

The ever increasing electric applications in aircraft add to the desirability of an adequate flexible method of evaluating loads under practical operating conditions. The method as described in this paper has proved very satisfactory and reliable for this purpose, and when used in conjunction with the other influencing factors it serves well as a basis for selection of generators and batteries.

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2. AIRCRAFT ELECTRICAL ENGINEERING (book), Randolph Matson. McGraw-Hill Book Company, Inc., New York, N. Y., 1943, pages 136–9.

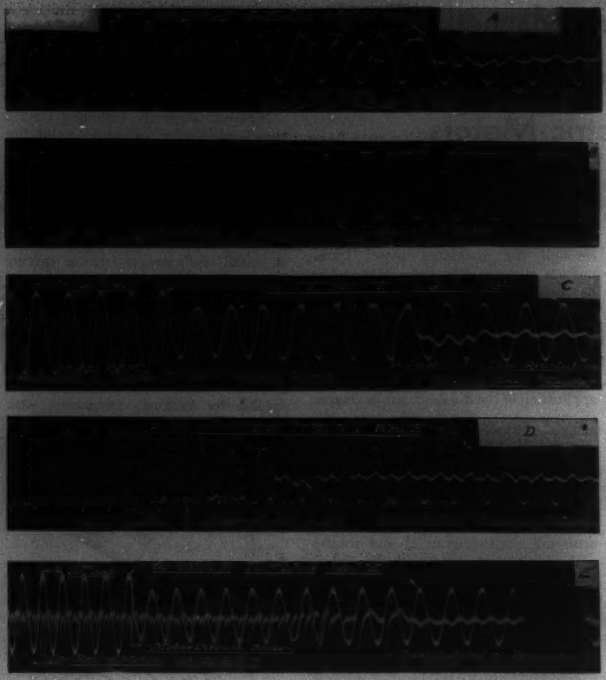

Figure 3. Performance of brake

A. Motor data—450 watts; 24 volts; 30 amperes; weight, 5.6 pounds
B. Motor data—100 watts; 24 volts, 8 amperes; weight, 3.25 pounds
C. Motor data—75 watts; 24 volts; 8 amperes; weight, 1.9 pounds
D. Motor data—30 watts; 24 volts; 4 amperes; weight, 1 pound
E. Motor data—30 watts; 24 volts; 4 amperes; weight, 1 pound

while the relatively heavy armature is allowed to coast to a standstill.

Small 24-volt d-c motors with spring-actuated brakes in the output range of 0.02–0.08-inch-pound torque have been reversed as many as 18 times per minute on plugging duty without failure over 60-hour intervals.

The braking performance of a group of high-speed motors ranging in output from 35 to 500 watts is shown in the oscillograms of Figure 3. The accompanying data inscribed upon the prints make the figure self-explanatory.

With the mushroom growth of war activities, this clutch, as is true of so many other new developments, like Topsy, "was not born, but just grew." The following sections entitled "Analysis of the Magnetic Circuit," and "Detailed Design," which have been explained in the foregoing paragraphs, are attempts to pause and consider what is happening in the devices. Concepts and design will be presented straightway with no further explanations and with the hope that they will form a background for further development.

Analysis of the Magnetic Circuit

Figure 4 comprises a part of Figure 2 (assembly) and is used to illustrate this analysis. The path of the magnetic circuit has been divided into five parts, designated as A, B, C, D, and E for the purpose of calculating a magnetization curve. It was developed by assuming different values of flux, then by calculating the ampere turns necessary to send each value through the various parts of the circuit. This curve is shown in comparison with a test obtained by means of a ballistic galvanometer and exploring coils in Figure 5.

Parts C and E have uniform cross-sectional areas. Parts A and D have varying cross-sectional areas. The procedure used in calculating the ampere turns required for a magnetic path with a varying cross section best can be explained by considering part D with an assumed total flux. This flux will be chosen as 12,000 lines, it being approximately the flux required to hold the clutch plates together when the motor is transmitting rated torque. Cross-sectional areas are determined for various locations; the corresponding flux densities are obtained by dividing the total flux by the areas; then from a magnetization curve of the material the ampere turns per inch are read.

The ratio of flux density per square inch to ampere turns per inch is the absolute permeability at the various cross sections. For a total flux of 12,000 maxwells Table I is made, in which NI is ampere turns, μ is absolute permeability, A is area in square inches, B is flux density in kilolines per square inch, and l is distance from the inside of the disk in inches.

If a graph of the absolute permeabilities at various locations is constructed the average absolute permeability can be determined by measuring the area and dividing by the length of the magnetic path. Such a graph is presented in Figure 6. The average permeability is found to be 9.745. Now from another graph of ampere turns per inch versus permeability, the ampere turns per inch are found to be 6.8. This value multiplied by the total length of 0.411 inch gives us a total of 2.8 ampere turns for part D. A summation of the calculations is shown in Table II. Adding to the ampere turns

Table II. Ampere Turns for Individual Parts of Clutch

	Lines of Flux				
	4,000	8,000	12,000	16,000	20,000
Part A	1.5	2.0	3.0	6	19.5
Part B	0.5	1.5	28.0	52	78.0
Part C	2.0	3.5	6.0	12	20.0
Part D	1.5	2.0	2.8	6	19.5
Part E	2.5	3.0	4.0	5	7.0
Total	8.0	12.0	43.8	81	144.0

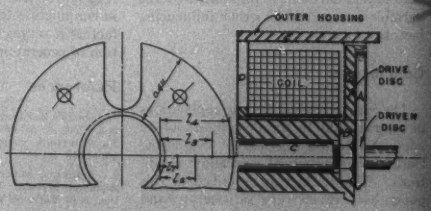

Figure 4. Sections of flux path

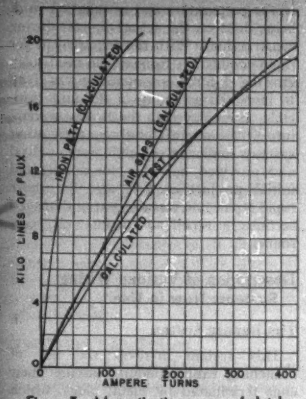

Figure 5. Magnetization curves of clutch

shown in Table II, those necessary to send the assumed values of flux through the air gaps, complete data for the magnetization curve are obtained, as presented in Table III, from which the curves in Figure 5 are drawn. Part B has a section in the drive disk which becomes saturated when approximately 8,000 lines of flux are passing through the circuit. Beyond this value some of the flux crosses the air gap into the nut on the shaft.

There are two air gaps to consider in a general analysis. One is the gap between the inner housing and the drive disk or between parts E and A. The other is between the drive-disk hub and the core or between parts C and D.

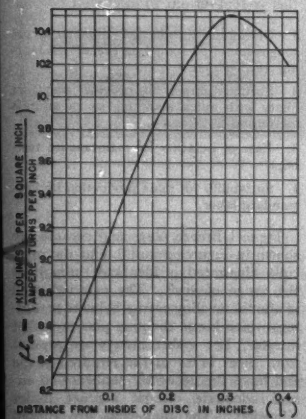

Figure 6. Absolute permeabilities of clutch-coil mounting plate

Table III. Summary of All Data

Lines of Flux	4,000	8,000	12,000	16,000	20,000
Ampere turns, iron path (calculated)	8	12	46	76	144
Ampere turns, air gaps (calculated)	52	104	156	208	260
Ampere turns, total (calculated)	60	116	202	284	404
Ampere turns (test)	50	110	185	285	440

Calculated flux densities expressed in kilolines per square inch in the designated parts with a total flux equal to 12,000 maxwells are as follows:

A	B	C	D	E
52 to 84	79	80	52 to 84	44

Detailed Design

The dimensions as indicated in Figure 2 will be used.

Moment of inertia of driven disk (comprised of two sections, the moments of which are computed separately):

$$V=\frac{D^2\pi}{4}\times\text{thickness}$$

$$W=0.28V \text{ (for steel)}$$

$$I={}^1/_3\times{}^1/_{12}\times W/g \text{ pound-inch-seconds}^2 = M/24$$

KINETIC ENERGY

$$KE={}^1/_2 I\omega^2={}^1/_2 I\times\left(\frac{2\pi N}{60}\right)^2=\frac{I\pi^2N^2}{1{,}800} \text{ inch-pounds}$$

Determination of brake spring force to stop disk in R revolutions.

A point on the average braking circumference of the driven disk moves RD_b inches.

$$F_1=\frac{KE}{RD_b\pi} \text{ pounds}$$

$$F_2=\frac{F_1}{C_b} \text{ pounds}$$

DISENGAGING TIME

Axial acceleration at disengagement due to $F_2=\frac{F_2}{M}$ inch-seconds.

$$t=\sqrt{\frac{2d}{F_1/M}}=\sqrt{\frac{2dm}{F_2}}$$

DISENGAGING SLIP

$$S=\frac{tN}{60}$$

Determination of flux required to pull driven disk into engagement with driving disk at no load:

$$F_3=\frac{B^2A}{72\times10^6}$$

or

$$B=\sqrt{F_3\times72\times\frac{10^6}{A}}$$

Likewise, the flux required to hold the disks together at any load is calculated as follows:

$$F_3=\frac{T_c}{C_c}$$

$$F_3+F_2=\frac{B^2A}{72\times10^6}$$

$$B=\sqrt{\frac{(F_3+F_2)72\times10^6}{A}}$$

Notation

A, area of clutch face of driving disk, $D^2\pi/4$ square inches
B, flux density, maxwells per square inch
C_c, coefficient of friction, clutch
C_b, coefficient of friction, brake
D, diameter of driven disk, inches
D_b, diameter of braking-ring material, average, inches
d, clutch clearance (between disks) maximum, inches
F, frictional force on brake, pounds
F_3, spring force, pounds
F_3, clutch force required to transmit torque, pounds
g, acceleration due to gravity, 32.2 feet per second per second
I, moment of inertia, pound-inches-seconds^2
KE, kinetic energy, foot-pounds
M, mass, pounds
N, motor speed, rpm
S, disengaging slip, revolutions
R, revolutions
t, disengaging time, seconds
T_c, torque to be transmitted by clutch with any applied load, pound-inches
V, volume, cubic inches
ω, angular velocity, radians per second
W, weight, pounds

Conclusion

To fill a long-standing need for clutch and brake development for electric motors, and because this need has been augmented and specialized by our current war-airplane manufacturing program, it seems imperative that the magnetic circuit, flux densities, mechanical and electrical forces, and in addition, the best magnetic coil dimensions be studied in order to perfect the most efficient design of this type mechanism.

It is hoped that this paper will be instrumental in breaking the ground for future development along these lines.

Electric-Wiring Installations in British Aircraft

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NONMEMBER AIEE

Synopsis: This paper deals with the growth of aircraft electric-wiring installations consequent upon the increasing use of electrical equipment in combat aircraft of all types. A brief description is given of the various proprietary and prefabricated systems of wiring in current use in British aircraft. It concludes with a description of the principles of the standard system now in an advanced state of development which will be applied to all new types of British aircraft now in the design stage.

THE increasing use of electrical equipment in modern aircraft has in its train focused attention on the distribution system. The major items of electrical equipment in British aircraft generally are supplied to the aircraft constructor as government-approved items. It will be obvious that their correct functioning depends upon the wiring installation which serves them. The size, shape, and equipment layout of an airplane does not lend itself readily to an orderly and well-spaced electric installation. The concentration into certain relatively small areas, peculiar in shape, of a large number of electrical items concerned with navigation, control, offense, and defense, is inevitable and constitutes a major problem for the designer. It is perhaps difficult to appreciate that in a modern four-engined bomber, some $4^1/_2$ miles of single-core electric cable would be required and in a fully equipped two-engined aircraft, $2^1/_2$ miles would be used. The problem of accommodation and efficient installation of this amount of wiring demands careful thought and planning. It is unfortunate that even up to the present day too little thought has been given to providing an orderly and well-engineered wiring installation and to ensuring well-protected cable routes. The impression still persists in some quarters that electric cables, being flexible, can be moved and disturbed at will to give pride of place to other more clamorous demands. This has resulted in wiring being "slung in" and is responsible for a high percentage of electric failures directly attributable to faulty location of wiring and equipment in situations where ingress of moisture, mechanical damage by air crew, and deterioration by extreme heat all have made their contributions. The Ministry of Aircraft Production, Directorate of Technical Development, now has specified design requirements in this connection which should mitigate, if not entirely overcome, such trouble in future installations.

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Elementary Wiring Installations

It was formerly the practice in British aircraft carrying a relatively small amount of electrical equipment, to employ a simple point-to-point system of wiring using single-core cables and the form of terminal block illustrated in Figure 1. This terminal block consists of a bakelite moulding having metal inserts carrying a terminal screw and captive washer. The terminal nests are of the shrouded type, enabling the bared end of the cable to be formed around the terminal screw thus preventing the straying of strands of wire to adjacent points; a simple cover completes the assembly. Such blocks are provided in a useful variety of ways and capacities.

With the growth of the electric installation, this system tends to become cumbrous, involving practically the whole of the preparation and installation work being done on the actual aircraft during construction. With the requirement for rapid production to meet the needs of a growing air force, consideration was given to increased assembly of the unit principle, as employed in the Breeze system, into British aircraft. Subsequently other systems similar in principle were evolved and provided not only for accelerated initial production, but also for more rapid repair and replacement of damaged sections by repair and maintenance personnel.

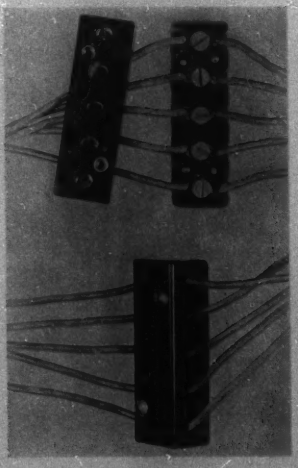


Figure 1. Typical terminal block (old pattern)

Description of Various Wiring Systems Now in Use

The Breeze System

This system involves the use of branching cable conduits having their ends terminated by metal plugs, which upon assembly into the aircraft are inserted into sockets carried on panels or junction boxes previously installed as completely wired assemblies.

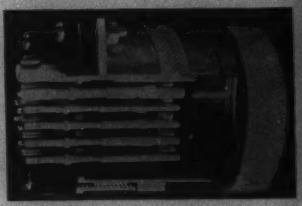


Figure 2. Breeze plug and socket for 7-, 19-, and 37-ampere conductors

The conditions which the designers of this system set out to meet were:

1. Minimum installation time to avoid congestion of personnel on the aircraft during construction.
2. Sectionalization to provide transport joints with quick matching up of aircraft sections.
3. Ease of isolation for maintenance testing.
4. Suitability for mass production by low-standard labor.

Typical Breeze plugs and sockets are shown in Figures 2 and 3, and the principle illustrated is identical throughout the range of sizes. The external shell of aluminum alloy carries bakelite mouldings which house the plug pins or socket inserts. The socket inserts are pressed from sheet brass to the required shape and have the necessary resilience to ensure adequate electric contact under vibration. The plug pins are turned from brass rod or alternatively are "bumped up" from brass wire.

The earlier Breeze installations em-

ployed flexible metallic conduits but the present practice is to use polyvinyl-chloride conduits except in the few cases where local screening is a requirement. General screening is achieved by suppression at the source of interference.

Figures 4 and 5 show a Breeze-wired main electrical panel for a heavy bomber, and a typical Breeze junction box, respectively.

The original Breeze installations employed soldered or screwed-down connections throughout, but more recent installations have incorporated the form of quick release connector block shown on Figure 6. This connector incorporates a solderless (crimped) spade terminal at the cable end.

The Lucas Loom System

This system was developed to provide a lightweight system of wiring components and prefabricated looms primarily for installation in fighter aircraft. It differs from the Breeze system in that conduits normally are not used, as the cables are whipped or bound into looms without additional protection. Quick-release connector blocks take the place of plugs and sockets, except in situations where a plug and socket is the more appropriate form of connector to employ. The connector block and other details are shown in Figure 7. The connector block consists of a bakelite moulding designed as a three-way junction. The actual electrical connections take the form of a metal socket split along its longitudinal axis and having pressure maintained by a central spring-loaded

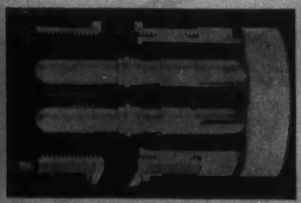


Figure 3. Breeze plug and socket for 64-ampere conductor

screw. Sockets may be either of single-tier or double-tier type. A series of connector blocks is built up as required into a bank by means of a tie rod as illustrated. Backing strips and covers are provided to prevent accidental short-circuiting of connections, and fixing feet are added as necessary.

The prepared ends of incoming cables are soldered to metal nipples and these nipples act as the plug for insertion into the split sockets.

The procedure adopted for installation of this system into aircraft is as follows. The cable looms for each section of the aircraft (see typical examples in Figures 8 and 9) are suitably whipped and attached to plywood transport boards. These boards are carried into the aircraft, the lashings cut, and the loom run out into position and cleated to prepared positions on the air frame. The nipples are then inserted into the sockets on the connector blocks which previously have been installed in selected positions. Connector blocks and cable ends are identified appropriately to insure correct assembly. Final tightening of the central connector screw on the block ensures a reliable electrical junction.

The Strip System

The rapid increase in aircraft production imposed an increasing strain on the already overloaded facilities available for the production of the Breeze and Lucas systems. The principal difficulty was in the number of machined parts required and the making up of the conduits or looms. As a means of overcoming these difficulties and to cater to the requirements of new types of aircraft coming into production, the strip system was introduced. The feature of this system was that it relied more on pressed than on turned parts and employed multicore cables instead of conduits or looms. The name "strip system" was derived from the comprehensive use of a ten-way connector of strip form.

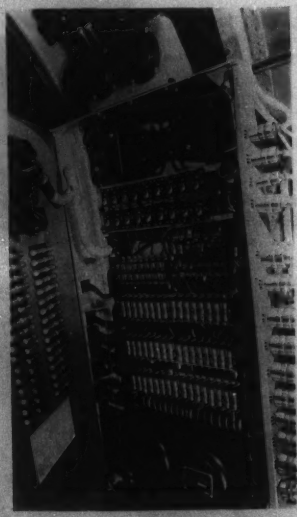


Figure 4. Breeze panel, typical aircraft assembly

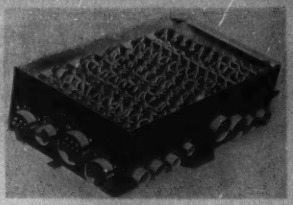


Figure 5. Typical breeze junction box

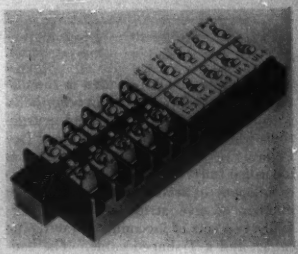


Figure 6. Breeze 20-way terminal block

The ten-way strip connector consists of pressed-copper contacts, silver-plated and gold-flashed, attached securely to a laminated bakelite strip. The contacts are located in slots in the bakelite strip (see item 9 of Figure 10). Between the interior surfaces of the contacts and nested in the central holes in the bakelite strip are stainless-steel springs to provide necessary contact resilience. Two assembly holes—one square and the other round—are provided in the bakelite strip. The prepared ends of the ten-core cable are soldered to the contact-strip extremities.

Five sizes of ten-core cables are provided for main-trunk lines and comprise an intelligent arrangement of 4-, 7-, and 19-ampere cores; rubber dielectric is employed and the exterior sheathing is polyvinyl-chloride.

Item 1 of Figure 10 shows a made-up cable assembly complete with its identification markers and the necessary rubber grommet for attachment to a distribution or junction box.

The distribution and junction boxes vary only in that the former carries fuses whereas the latter is purely a "break" box. Figure 11 shows typical junction boxes for this system. The larger box has a bakelite base, teak sides, metal slides for accommodation of cable grommets, and a metal cover. The small box is an aluminum die casting. Covers of all boxes are provided with double gauze-protected breathing holes.

On installation in the aircraft, the strip connectors with cable attached are

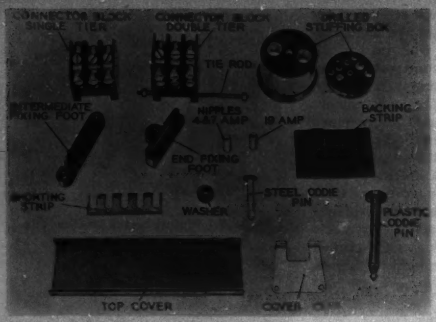


Figure 7 (left). Lucas loom-system components

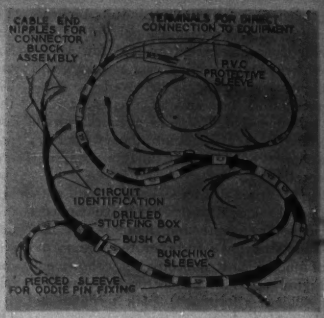


Figure 8 (right). Typical Lucas loom

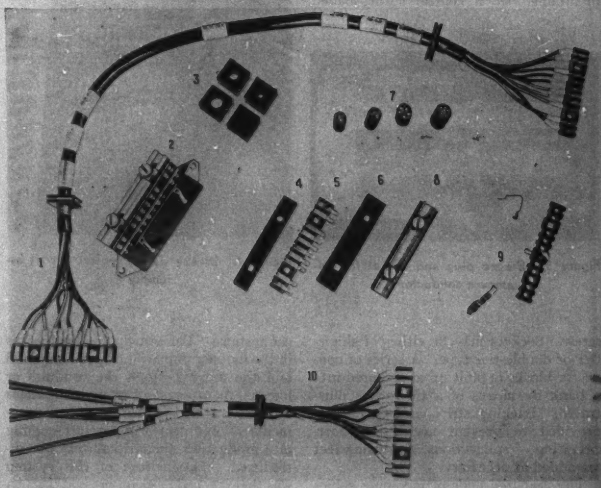
assembled on pillars provided in the distribution or junction boxes in accordance with a few elementary rules and instructions which appear on the box cover (see Figure 12). Assembly order therefore is identified fully. The height of the pillars is sufficient to accommodate a maximum number of five strips connector—normally two sets of incoming and outgoing cables and a T-shaped cable. The connector strips have their short ends painted either "red" or "white" and like colors always must be in physical contact and insulated from unlike colors. The action of screwing down ensures efficient electrical connection between connector strips. When less than the maximum number of five strips are assembled, the space remaining is made up by the use of bakelite backing strips (see item 4 of Figure 10). Local single-core cables are attached to the strip connectors in similar manner to the main ten-core cables as shown in item 10 of Figure 10.

The principle of application of the strip system is similar to that employed for the Breeze and Lucas systems. Looms of multicore and local cables complete with their strip connectors all appropriately identified are brought into the aircraft, and cleated into position on the airframe, and finally the strip connectors are assembled in the distribution or junction boxes previously installed.

Standard spare lengths of ten-core cable assemblies are available for replacement and repair purposes.

Figure 9. Typical Lucas loom installed on aircraft

Figure 10 (below). Strip-system components



Development of the Standard System

The wiring systems just described have given reasonably good service under wartime conditions, but the existence of at least three distinct and varying systems of wiring presented difficulties of maintenance and storekeeping which can well be imagined. Consideration therefore has been given to the development of a standard system of wiring which could be applied comprehensively to all new types of British aircraft. The existing systems were examined critically to ascertain whether any of them could be adopted as the approved standard, but it was found that each exhibited weaknesses of greater or lesser degree. The Royal Air Force and Fleet Air Arm representatives were consulted on their experience of actual field conditions and expressed a strong preference for stand-

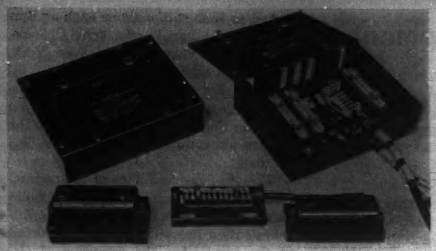


Figure 11. Typical strip-system junction boxes

ardization of a system akin to the Lucas loom system but with improvements in insulation value, resistance to corrosion, and maintenance facilities. This recommendation formed the basis on which development proceeded under the guidance of a committee representative of the Society of British Aircraft Constructors, the electrical industry, and the Directorate of Technical Development of the Ministry of Aircraft Production. The development of the standard system and components is not yet completed in every detail, but the following is a description of the main principles and component parts:

1. The main points which needed to be borne in mind during this development were: simplicity of engineering, ease of production, flexibility to accommodate modifications, economy of weight and space, efficiency under all conditions of operations. The system is based on the use of single-core cables for general wiring, the reduction to the minimum of junctions and joints, and the use, as generally as possible where breaks are essential, of efficient connector blocks.

2. Connector blocks for cables up to and including 37-amperes capacity are of the "quick-release" form. A typical 19-ampere block is shown at Figure 13. It will be noted that this block conforms closely to the principle of the Lucas block and comprises a bakelite moulding dimensionally designed to give the maximum creepage path consistent with reasonable size and weight. Apertures right through the block ensure free circulation of air, drainage of deposited moisture, and rapid drying. Molded-in inserts are provided for the reception of socket assemblies, either single- or double-tier as illustrated. The sockets are split along the longitudinal axis and pressure is controlled by a spring-loaded screw. All metal parts employed are noncorrodible.

3. The 19-ampere blocks will be available in 2-, 3-, 5-, and 15-ways and covers are provided for use when required. Identical in principle, the 37-ampere blocks are slightly larger and are available in two- and three-ways.

4. Cable ferrules similar to the Lucas nipples are attached to the cable ends by being crimped to both the cable core and the dielectric, providing thereby a rigid bond and support for the joint.

5. For cables of 64-ampere capacity and larger, a heavy-duty connector block will be provided. This consists of a bakelite moulding having a molded-in central pillar and a recess for the reception of the cables. Pressed cable lugs of the palm type are employed. These are assembled as required on the central pillar and securely clamped by a lock nut. There are no multiple combinations of this block. Attachment of lugs to the cable core normally is done by clamping, but soldering is also demanded and preferred.

6. Suitable hand crimping tools have been designed for attaching ferrules and lugs, but it obviously will be necessary to consider bench and power-operated tools when full production of the system arises.

7. Junction boxes will not be used in connection with the standard system in situations where the aircraft structure or a cover of simpler form than a box (for example, a canvas cover) provides sufficient protection for banks of connector blocks. For exposed positions, however, or in situations where mechanical damage is possible, standard boxes will be provided which are designed to be splashproof and capable of draining away any accumulation of moisture due to internal sweating.

8. Fuses generally will be mounted on panels and designs are in hand for combined fuse holder and connector blocks to cover the standard fuse range up to and including 100 amperes. Above that capacity it is probable that circuit breakers of the trip-free type will be used. A standard identification scheme also has been produced concurrently with the foregoing development and will become an integral part of the standard system.

9. Cable looms will be prepared external to the aircraft and installed in similar manner to that outlined for the Lucas system. The electrical installations for new types of aircraft now being designed will employ the standard system.

Cables

Hitherto on British aircraft, there has been a general use of "cel"-type cables. These cables employ cellulose-lacquered cotton cambric as the external sheath and rubber as the dielectric. In the past "cel" cables have given reasonably good service, but there has been difficulty under wartime production conditions in ensuring the necessary high-grade finish of the sheath to resist attack by gasoline, oil, and hydraulic fluid. There is now a tendency to employ polyvinylchloride as the external sheath in view of its high resistance to action by these fluids.

A further development now in the initial stages has been occasioned by the gradually deteriorating quality of the rubber permitted for use as a dielectric. From this development sample cables employing polythene as the dielectric have been produced and appear to be

Figure 12 (left). Typical strip-system aircraft assembly

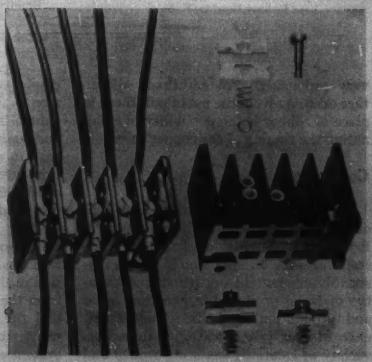


Figure 13 (right). "Standard" system five-way, 19-ampere connector block

Airline Aircraft Electric-Equipment Maintenance

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"ANNOUNCING the departure of trip 23, Nashville–Memphis–Phoenix–Los Angeles, leaving at gate 6, all aboard, please." In a matter of minutes after this announcement an airliner departs on schedule to carry some 5,000 pounds of passengers and cargo over rivers, mountains, and cities and to deposit them safely at the destination. Another routine flight has been made possible by the combined efforts of a small army of airline employees.

Electrical engineers will be interested to know that a large part of the success of the trip is the result of their efforts in the development of reliable aircraft electric equipment. So dependent is the present-day air transport upon its electrical equipment that without it airline operation as it is known today would be quite impossible.

The foregoing statement is not to be misconstrued to mean that an aircraft's electrical system is essential for successful flight, since in aeronautical terminology, a distinction is made between the engine electric-accessory equipment necessary for engine operation, namely, magnetos, booster coils, ignition wiring, and so forth, and the remainder of the electric system such as the generators, instruments, lights, radio, and similar equipment. Although it is entirely possible to take off and fly an airplane without the aid of any of the latter equipment, long-distance flights or even flights extending beyond the visibility of the airport would be extremely hazardous except under the very best conditions of daylight flight, with ceiling and visibility unlimited weather, and freedom from icing conditions.

It is the purpose of this paper to present the airline operator's problem of insuring reliable operation of the aircraft electric equipment. This problem will be presented from the standpoint of operation of American Airlines' fleet of 50 Douglas *DC-3* transport airplanes, the conventional 21-passenger low-wing all-metal monoplane. The following statistics will give some idea of the magnitude of the problem. During the year of 1943 to 1944, some 449,556,248 passenger miles were flown with an average flying time of 10.2 hours per day per airplane. This flying was done over 8,369 miles of routes extending from New York to California and from Canada to Mexico and serving some 45 cities in that area.

A glance at the organization chart of American Airlines' maintenance department (Figure 1) will show the arrangement which has been found necessary to accomplish the job of maintaining a fleet of airplanes. It is impossible to discuss the problem of aircraft electric-equipment maintenance without considering the entire system, inasmuch as the basic maintenance procedures are formulated from the operating experience with all components of the airplane and are carefully planned to produce the maximum effect with the minimum cost. The following is a thumbnail sketch of the maintenance system and procedures.

Briefly, there are four stations designated as base stations, one each at Burbank, Calif.; Fort Worth, Tex.; Chicago, Ill.; and La Guardia Field, New York, N. Y. In addition all the overhaul facilities: shops, engineering, and administrative departments are located at La Guardia Field. All other stations in the system are commonly referred to as line stations.

The chief responsibility of the maintenance department is to keep the airplanes airworthy. The Civil Aeronautics Administration has outlined in some detail in the regulations the definition of airworthiness as it applies to all parts of the airplane. A unit of equipment designated as airworthy obviously must have a certain degree of reliability. The reliability of an article can be controlled to some extent by the application of inspection and overhaul procedures; however, the application of such procedures increases the cost of operation and some economic and workable balance must be obtained.

The airline's yardstick of service is the hour. One hour of service on a part means that it has flown for that period of time clocked from wheels off to wheels down and represents approximately 155 very promising. An additional advantage accruing from the use of polythene in place of rubber is the possibility of eliminating the tinning of the copper cores.

Table I. Electric-Equipment Overhaul Time Table

Equipment	Overhaul Period Normal	Maximum
Generator control box	400	425
Landing-light bulbs	400	460
Starter motor	Every engine change*	
Propeller-deicer pump motors	Every engine change	
Generators	Every engine change	
Tachometer indicators	Every engine change	
Carburetor-temperature bulb	Every engine change	
Oil-temperature bulb	Every engine change	
Thermocouple washer	Every engine change	
Exhaust-analysis cell	Second engine change	
Tachometer magneto	Second engine change	
Voltammeter	Second engine change	
Pitot-heater ammeter	Third engine change	
Fuel-quantity indicator	Third engine change	
Exhaust-gas-analyzer indicator	Fourth engine change	
Air-temperature gauges	Sixth engine change	
Carburetor-temperature gauges	Sixth engine change	
Cylinder-head-temperature gauges	Sixth engine change	
Fuel-quantity tank units	Sixth engine change	
Oil-temperature gauges	Sixth engine change	
Synchroscope	Sixth engine change	
Starter relays	1,500	2,000
Argon-light dynamotor	1,500	2,000
Wing-deicer valve motors	1,500	2,000
Flasher mechanism, navigation lights	3,500	3,750
Pitot heater	4,500	5,000
Master switches, battery	5,000	6,000
Primer solenoids, booster coils	5,000	6,000
Fuel-flowmeter power supply	5,000	6,000
Landing-light relays	6,500	8,000
Electric system, including conduit, wiring, junction boxes, lights, switches, and so forth	(Airplane overhaul) 6,500	8,000
Batteries	Life of battery	

* Engine-change period—normal—750 hours; maximum—775 hours.

Conclusion

From the foregoing it will be seen that developments are proceeding actively in Britain to provide electric-wiring installations for aircraft which will be reasonably efficient in operation and capable of being produced by wartime labor and production methods. The experience of four years' war operations in a variety of locations has been studied and employed as the basis for this development. Among these experiences is that gained by British personnel in operating and maintaining American types of aircraft in which single-pole electric installations are employed. Although until recently all British aircraft employed an insulated two-pole system, new types of aircraft are being engineered on the single-pole system employing the air frame as the negative return. The adoption of this practice will be advantageous from the points of view of weight saving and the ability to use electrical equipment which has been designed for this system of supply.

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miles of flight. Every airplane is subjected to a total of four types of inspection and one period of overhaul. The most frequent inspection is the service inspection which is conducted at every regular schedule stop and which consists of a visual check of the airplane's control surfaces and propeller blades, and a check of the oil and gasoline in the tanks. At that time any pilots' complaints are acted upon where necessary to render the aircraft airworthy. This inspection will occur on the average of every two hours of flying time and approximately four times a day for each airplane.

The next regular inspection is designated as a line or base inspection, depending upon whether the aircraft is at a line or base station. This inspection is given to every airplane which has terminated its flight schedule or if a flight has been cancelled for a period of ten hours or more. Two men spend approximately five hours in making a comprehensive visual inspection of the aircraft's exterior and of its interior accessory equipment. At this time a functional check of the electric system is made, and the airplane's storage batteries are replaced with freshly charged batteries. All units are checked for their replacement time and are changed if necessary. Each aircraft receives a line or a base inspection at least once every 24 hours (Figure 2). A base inspection is essentially a duplication of the line inspection with the addition of a few more complete functional checks made possible by the use of test equipment located at the base stations. Approximately 75 items of equipment are reviewed at the time of a base inspection.

A major inspection is given each aircraft when 200 hours of flight time have been accumulated with a maximum limit of 230 hours since the last major inspection. A major inspection is performed at a base station and requires approximately 100 man-hours. It is a repetition of the aforementioned base inspection with the addition of a functional check of the hydraulic and landing-gear system with the ship on jacks. A more comprehensive engine inspection is made and consists of an oil change and a check of the valve clearance and of cylinder compression. The calibration of the exhaust-gas analyzer (fuel–air-ratio indicator) is checked by passing a test gas of known ratio through the analysis cell (Figure 3). The major inspection covers some 100 items of the aircraft.

In addition to the various airplane inspection periods the maintenance procedure requires that every component of equipment be overhauled periodically. The time between overhaul for any accessory is determined primarily by the past service experience with that equipment. Furthermore, wherever possible this time is adjusted to coincide with one of the inspection or engine-change periods. As it turns out most of the periodic replacement times are equal to or multiples of the engine-change period. This period at the present time is 750 to 775 hours. Those electric accessories which form a part of the engine-mount assembly are expected to give reliable service for at least the engine-change period, thereby facilitating the handling of such parts during their replacement. These units include the aircraft engine-driven generators, starter motors, magnetos, booster coils, resistance-type temperature bulbs, and tachometer generators. The engine spark plugs are the outstanding exception to this program, requiring replacement every 60 hours.

Other electric equipment not necessarily a part of the engine assembly also is removed during engine-change periods and at various multiples thereof. Table I indicates the various times at which the different items of electric equipment are removed for overhaul.

It is interesting to note the increase in engine-change periods during the past six years as this is a factor which directly affects the periodic replacement time for the majority of electric equipment (Figure 4). That is, if the overhaul time of various accessories could not be advanced with the engine-change time, the entire maintenance program would be seriously inconvenienced. There has been some discussion in regard to raising the engine-change time to 1,000 hours, and it is not unreasonable to expect such a change in the next few years. In view.

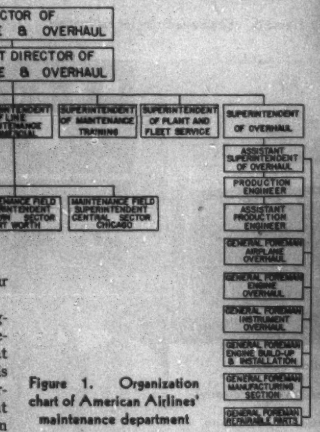
DIRECTOR OF MAINTENANCE & OVERHAUL
ASSISTANT DIRECTOR OF MAINTENANCE & OVERHAUL
SUPERINTENDENT OF LINE MAINTENANCE MILITARY
SUPERINTENDENT OF MAINTENANCE GENERAL OFFICE
SUPERINTENDENT OF MAINTENANCE INFORMATION
SUPERINTENDENT OF LINE MAINTENANCE COMMERCIAL
SUPERINTENDENT OF MAINTENANCE TRAINING
SUPERINTENDENT OF PLANT AND FLEET SERVICE
SUPERINTENDENT OF OVERHAUL
ASSISTANT SUPERINTENDENT OF OVERHAUL
PRODUCTION ENGINEER
ASSISTANT PRODUCTION ENGINEER
GENERAL FOREMAN AIRPLANE OVERHAUL
GENERAL FOREMAN ENGINE OVERHAUL
GENERAL FOREMAN INSTRUMENT OVERHAUL
GENERAL FOREMAN ENGINE BUILD-UP & INSTALLATION
GENERAL FOREMAN MANUFACTURING SECTION
GENERAL FOREMAN REPAIRABLE PARTS
MAINTENANCE FIELD SUPERINTENDENT EASTERN SECTOR NEW YORK
MAINTENANCE FIELD SUPERINTENDENT WESTERN SECTOR FORT WORTH
MAINTENANCE FIELD SUPERINTENDENT CENTRAL SECTOR CHICAGO

Figure 1. Organization chart of American Airlines' maintenance department

Figure 2. Battery service at line inspection

Figure 3. Exhaust-gas-analyzer-cell installation

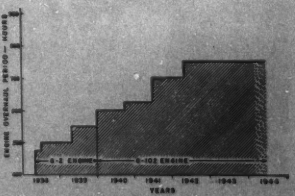

Figure 4. Trend of engine-overhaul period
Wright G-2 and G-102 engines

Figure 5. Fuel-flowmeter calibration

Figure 6. Engine-tachometer calibration

Figure 7. Electric-instrument overhaul

Figure 8. Electric-instrument calibration bench

Figure 9 (right). Bench test of electric-motor-driven accessories

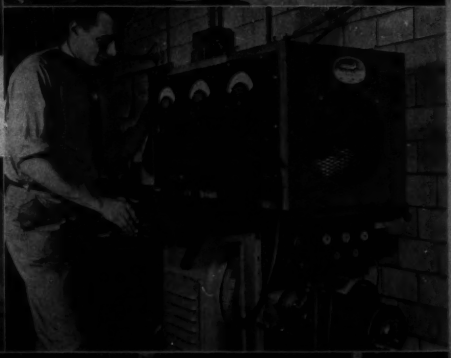

Figure 10 (lower right). Generator and control-box test stand

Figure 11 (above left). Starter-motor test stand

Figure 12 (left). Magneto test stand

Figure 13. Spark-plug overhaul

Figure 14. Electric-instrument-panel removal at overhaul

Figure 15 (top). Center section, electrical junction box

Figure 16. Pilot's electric switch panel

Figure 17. Main electric junction box

Figure 18. Rear view of instrument panel of Douglas DC-3 airplane

Figure 19. Individual-seat-light installation

Figure 20. Fabricating electric conduit for replacement

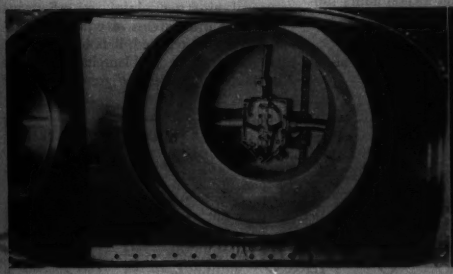

Figure 21. Landing-light installation of the leading edge of the wing

Figure 22 (above right). Engine electric-harness overhaul

Figure 23 (right). Engine ignition-harness overhaul

Figure 24. Space available for servicing engine electric accessories

of this trend in engine-change period, it is somewhat disappointing to note the newly created Army–Navy and other specifications setting the continuously operating time requirement for accessory equipment at 400 hours. It sincerely is hoped that the aircraft electric-equipment manufacturers will design for the 1,000-hour mark so that their equipment will fit in with the expanding airline requirements. In this respect the manufacturer should consider that the airline operator must balance maintenance cost against the operating cost and that, in some instances, the heavier but less troublesome article is the less expensive in the long run.

The actual overhaul procedure to which each unit is subjected is determined largely by the service experience with the unit. However, in many cases it corresponds 100 per cent with the manufacturer's service instructions. Figures 5 through 13 illustrate typical overhaul procedure on a number of electric items.

After approximately 6,500 hours and not more than 8,000 hours of operation the airplanes are brought in to New York for a ship overhaul. In addition to all the structural inspection and repair the remainder of the electric system, namely, conduit, wiring, junction boxes, switches, and so forth, is inspected and replacements are made where necessary (Figures 14 through 23). In general the aircraft conduit and wiring in the engine nacelle compartment must be changed at this time. The fuselage conduit and wiring, however, has been found in satisfactory condition after 18,000 hours (approximately five years) of service. The wire in the engine section, commonly referred to as the engine harness, must be replaced at each engine-overhaul period.

Up to this point we have discussed the ideal maintenance procedure in regard to inspection and replacement of equipment for overhaul. Supplementing this problem is another in which provision has to be made for replacement of units which fail in service. Briefly the problem is one of stocking a sufficient number of spare units at strategic stations, the number of units and stations being determined from past experience, so that flight schedules will suffer a minimum of interruption. In addition some means must be provided for returning the used part to New York where it will be overhauled and returned to service. In order to expedite the movement of these parts, it is necessary to ship 60 per cent of them by airplane to New York. It might appear on the surface that the airlines are saving themselves a transportation bill; however, such reasoning is fallacious inasmuch as the present operation at high-load factors places a penalty on any additional weight which does not result in an increase in revenue. American Airlines estimates the addition of one pound of such weight to cost approximately $88 per airplane per year.

It is because of the necessity for replacements of units in the field that the airlines have placed so much emphasis upon design of equipment and installations for ease of maintenance. It is important to note that design for easy servicing requires the co-ordination of both the equipment and the aircraft manufacturer. That is, an aircraft accessory can be designed with the most effective quick disconnect features, but, if it is so installed on the aircraft that it requires a removal of stress plates, miscellaneous lines, and other items of equipment before it can be reached, it is obvious that the maintenance problem has not been satisfactorily solved (Figure 24). The

Figure 25. American Airlines' daily operations chart

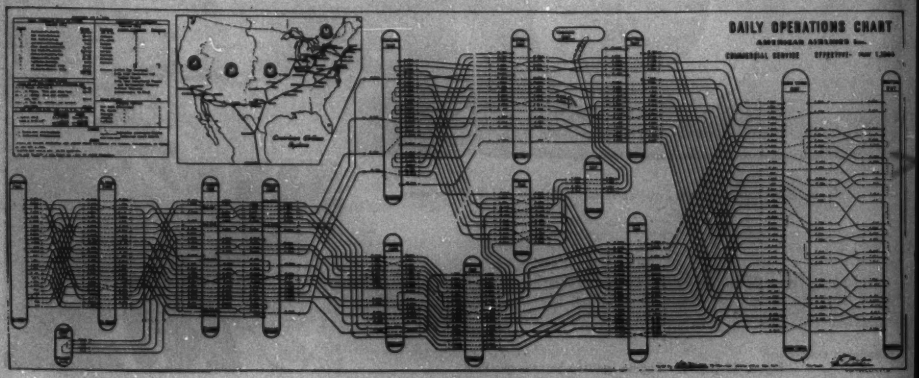

Figure 26. Airplane routing office

equipment manufacturer owes it to himself to follow up on the installation of his equipment in order to insure that the installation of his product is not unfavorable to its ready servicing. This is particularly important when the unit of equipment is of such nature that it requires frequent servicing. We might cite as an example the spark plug for which an installation was designed requiring the removal of considerable cowling. Removing one spark plug necessitated approximately nine man-hours of labor. As a matter of fact it is this type of design which is giving impetus to the creation of readily removable engine-mount assemblies, since it appears that it would be quicker to change the entire engine than it would be to change the spark plugs.

The entire maintenance system would be impossible without a smoothly running record and report system. The goal of this system is to record all changes and inspections made to the airplane and its parts so that it is possible to determine at any time when a part was removed or installed on an airplane; its identifying serial number; the mechanic who replaced the part; and the complete overhaul history of the unit, including the trouble found, correction made, and the mechanic who did the work. Some idea of the scope of this system can be gathered from the fact that there are some 65 parts in each airplane of which overhaul records are kept.

Equally important is the job of the maintenance dispatch office which has the responsibility of controlling the scheduling of airplanes so that they will be at their proper stations within the designated limits of time for inspection periods, engine-change periods, and overhaul periods. Some idea of the scope of this job can be obtained from Figure 25 which illustrates the various scheduled routes over the system. Each base station furnishes a daily report by radiogram listing the scheduled routing of all airplanes in its individual control sector. This information includes data on engine time since overhaul and time since the last inspection of the airplane. From this mass of data the maintenance dispatcher issues routing instructions which are designed to bring the airplane to an appointed station in time for this required servicing (Figure 26). In spite of the complexity of the system, the average engine-change time of 42 engines for the month of April 1944 was exactly 750 hours.

This discussion would not be complete without a word about the activities of the airline's engineering department and a brief description of its functions. In a broad sense the engineering department acts as a technical consultant to the maintenance department with the object of improving the service life of the equipment and thereby increasing the efficiency of the operation. A service-report system is utilized to keep both the maintenance and engineering departments informed of the current difficulties. These reports are initiated in the field at the time the trouble is experienced and include all pertinent information which will be of value in the determination of suitable corrective action.

Not only is the existing equipment under constant investigation for possible improvements, but also a weather eye is kept on the industry at large to utilize the fruits of improved design in order to obsolete less satisfactory equipment. It is the engineering department's responsibility to maintain contact with all parties concerned in the design and manufacture of the aircraft and to negotiate desirable improvements in any of the associated equipment. The organization of American Airlines' engineering department is shown in Figure 27 and illustrates the degree of specialization which is necessary in order to adequately cover the broad field of engineering which makes up the modern air-transport system.

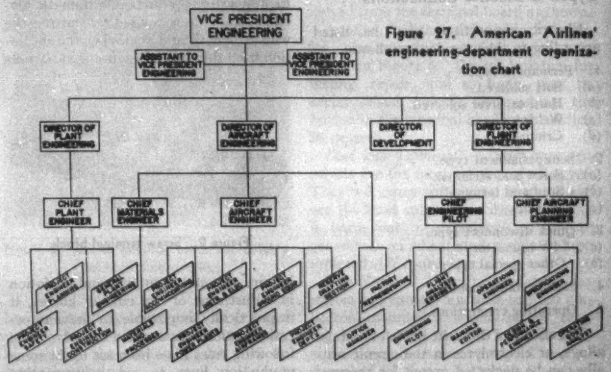

Figure 27. American Airlines' engineering-department organization chart

It is hoped that the foregoing discussion will have served its purpose of bringing home to the aircraft electric-equipment designer a picture of the end use of his product. More important, however, is the designer's recognition of the fact that his equipment must fall into a predetermined pattern of inspection and overhaul procedures which are not necessarily set up to accommodate his particular equipment but rather to provide an economical method of insuring the airworthiness of the complete airplane.

Electric Connections on Aircraft

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MEMBER AIEE

L. A. TAYLOR
NONMEMBER AIEE

AN electric system is as good as its electric connections. Poor electric connections on aircraft easily can cancel the tremendous advantages obtained by the use of electric systems. Little attention is given to this unglamorous but vital subject because of the more absorbing and interesting details of the electric system as a whole. Only after an unexpected and disconcerting electric-connection failure in service does the engineer realize its importance. Such failures on domestic appliances are not generally serious but on aircraft may involve many lives, much valuable equipment, and, in fact, the success of our war effort.

This paper describes factors and design details which must be considered in the design of successful electric connections on aircraft.

Types of Electric Connections

Electric connections may be listed according to their service as follows:

1. Permanent type.
(*a*). Soft soldered.
(*b*). Hard or silver soldered.
(*c*). Welded.
(*d*). Crimped.

2. Semipermanent type.
(*a*). Screw and terminal.
(*b*). Stud and terminal.
(*c*). Special.

3. Quick disconnect type.
(*a*). *AN* connector.
(*b*). Other special types.

4. Sliding connections.

5. Operating connections.

The effects of different kinds of metals, alloys, or electrolytes in the circuit usually can be neglected except for thermocouple and other similar low-voltage circuits. These exceptions require connections to be made with like materials, or they may require a design in which paired junctions are always at the same temperature. For example, a soldered joint making a connection between two copper wires will cause little difficulty when the two junctions are close together, except in the most critical circuits. Clamped or welded connections between like materials are required where undesired thermal electric voltages are to be avoided.

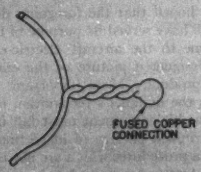

Figure 1. Flame-welded connection between two enameled wires with a twisted portion for mechanical support

Permanent Types

Soft Soldered. In spite of the fact that the art of soft soldering electric connections is relatively old in the electrical industry, it still must receive constant attention in production lines beginning at the point where the insulation is stripped from the wire.

The preliminary insulation stripping operation preferably should be accomplished without nicking, swaging or scrapping any strands in the wire. The insulation on aircraft wire per *AN-J-C-48* should be cut evenly, leaving the wire clean and free from insulation. For high-quantity production, automatic machines have been devised for cutting the wire to length and removing the insulation from the ends. Because of variations in wire size and stranding and variation in adjustment of the cutting knives, it is practically impossible to prevent occasional nicked or scraped strands. The following rules have been set up in some production lines to aid in inspecting stripped wires:

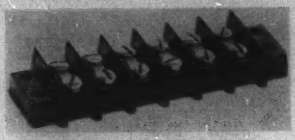

Figure 2. Screw terminal block

1. Not more than ten per cent of the number of strands can be nicked.

2. Strands which are scraped or swaged not more than 25 per cent of the diameter are acceptable.

3. If it is assumed that the nicked strands may break during assembly, the following maximum number of broken strands after assembly are allowable:

Strands in Wire	Maximum Allowable Broken Strands
7	1
10	1
16	1
19	2
26	2

Hand-operated wire insulation strippers may be used for laboratory purposes, service work, and so forth, but are subject to the same dangers of nicking and scraping.

The design of the wire insulating layers can have appreciable effect on the ease of stripping. The first or separator layer can be made of material such as number 400 electrical tape which will rupture readily and allow the other insulating layers to slide off the wires easily when they are cut. The stripping knives then can be set to the outside diameter of the wire plus the separator layer which reduces the possibility of damaging the wire.

Insulation also may be removed by burning with electrically heated blades at the desired point, allowing the insulation to cool, and pulling the insulation off the end of the wire. The interval for cooling is necessary so that hot and softened insulation, such as Flamenol, will not be forced between the strands.

Enamel can be removed safely from single fine wires, 0.004 inch or smaller by rubbing with fine emery or crocus cloth. Chemical means may be used to remove the enamel, provided the chemical is subsequently thoroughly washed off. The enamel on stranded enameled wire may be removed by heating the wire and dipping the hot portion into denatured alcohol.

After the insulation has been removed from the end of aircraft wire (per *AN-J-C-48*), it is preferable to twist the strands tightly together in a production twisting machine. They are then dipped into a rosin and alcohol soldering flux and into a solder pot. This extra "tinning" operation saves much time in a production line because the strands of the wire stay in place while the mechanical connection is being made.

When making connections between wires and vacuum-tube socket or similar terminals, the wire should be looped through eyelets or slots and wrapped around to give a mechanical support before soldering to the terminal.

The soldering operation is completed by applying flux, heat, and solder to the wire and terminal so that the solder wets the metal surfaces. The joint must cool so that the solder freezes solid before any strain is applied to the joint. Any relative movement between the wire and terminal during the freezing renders the connection mechanically and electrically weak.

Rosin or rosin in alcohol is the only flux which has proved satisfactory for aircraft electric connections. The minimum amount of flux should be used. Rosin-cored wire solder having rosin in

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Figure 3. British wire terminal having combination screw, crimped, and clamped features

five per cent or less of the cross-sectional area can be used conveniently. When soldering near electric contacts, care must be used to prevent the rosin from splattering or running onto the contacts. Excess rosin may flake off onto contact surfaces after it has dried out, which is an important reason for using the minimum flux. The soldered connection may be cleaned with alcohol to remove all excess rosin, or it may be coated with a colored lacquer or Glyptal paint to prevent corrosion and flaking of the rosin.

Excess solder on a joint is not only wasteful, but also may cover a poor joint. A beautifully rounded ball of solder on a joint is to be avoided. The form of the strands of wire should show on a well-soldered joint, with fillets of solder between strands and terminal indicating a thorough wetting by the solder.

Hard or Silver Soldered. This type of connection is normally used only on circuits which are subject to temperature higher than the softening point of the soft solders. It is very important that the fluxes be thoroughly removed to prevent corrosion in service.

Welded. Both spot and flame welding are used extensively for special connections. Spot welding requires a very high grade of control to insure satisfactory joints because it is difficult to determine the quality of the joint by visual or nondestructive means.

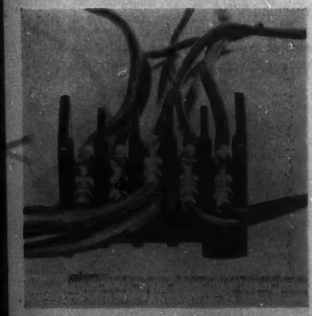

Figure 4. British terminal block using wire terminals having combination screw, crimped, and clamped features

One successful production method of connecting copper wires larger than 0.010 inch consists in twisting the wires together for mechanical support and melting the ends of the wire down to a ball with a hot flame as shown in Figure 1.

With Formex or enamel insulated wire, it is not necessary to remove the insulation when using this method.

Crimped. Several types of crimped connections have been developed for use between wires and terminals. These have the advantages of eliminating flux and solder troubles and speeding up production. Some types are crimped on both the wire strands and insulation to form a very good mechanical support. Standard crimped or solderless types for aircraft use are specified under Army–Navy Aeronautical Standard *AN*-659. One new type recently put on the market

Figure 5. British terminal block for quickly disconnecting circuits

has an insulating coating on the crimped portion which eliminates the necessity of covering the terminal shank with an insulating sleeve.

The quality of the connection obtained with solderless terminals is difficult to determine by visual inspection. The size of the terminals and crimping tools must be held to close tolerances which have been proved to produce satisfactory joints by destructive tests. The crimping pressures and the physical characteristics of the crimped tube must be carefully controlled. One type of crimping tool cannot be used with all makes of terminals because of differences in size and design. The National Aircraft Standards Committee and Army and Navy are taking steps to obtain standardized types and tools, but at the present time best results are obtained by using the tools and methods according to the terminal manufacturers' recommendations.

SEMIPERMANENT TYPES

Screw and Terminal. Screw terminals are used where space is restricted, and the currents are limited to about 30 amperes. Figure 2 shows one style which is used extensively. The number of connections which can be made under the head of a screw is limited by the length of the screw. Generally two connections are the maximum. It is also advisable to use a split spring lockwasher between the screwhead and connecting terminal.

A combination screw, crimped and clamped terminal connection used on British aircraft, is shown in Figures 3 and 4. This design has several obvious advantages in assembly and servicing. The wire terminal is a cylindrical design which is crimped on the wire and insulation. This is held by a simple screw-clamp arrangement which can be removed from the terminal board as shown.

Another British terminal block design for disconnecting circuits quickly is shown in Figure 5. Circuit isolation for testing, repair, and so forth, may be accomplished quickly by pushing the button in the terminal block and twisting 90 degrees.

Stud and Terminal. Stud-type terminals are the most reliable of all types. They will carry the highest currents and are the least subject to vibration. This is borne out by experience on aircraft generators on which stud terminals have replaced *AN* connectors.

The National Aircraft Standards Committee has issued standards on stud connectors mounted in special panels, ranging from number 6 screw studs to three-eighths-inch-diameter studs. These are described in National Aircraft Standards 17 through 22, inclusive.

A new type of stud terminal which clamps directly on the wire strands recently has appeared on the market and is shown in Figure 6. This eliminates the necessity of applying a terminal to the wire when making a connection, but the wire would be damaged if frequent removals from the stud were required.

Special. Ground connections or frame connections which are part of an electric circuit, and radio shielded con-

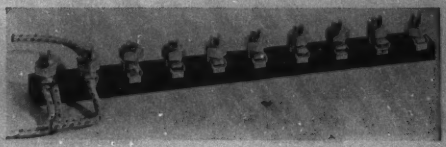

Figure 6. New type of stud terminal which clamps directly on the wire

Figure 7. Pin- and socket-type connector with "banana" pin construction

nections may be classified as special semipermanent types. In addition, many moving metallic parts on aircraft must be electrically connected together with low-resistance connections in order to reduce electrical disturbances which cause noise in the radio receiver. Special bonding techniques have been developed for making these connections. A flexible stranded bare cable with crimped or soldered terminals is generally employed. The connection between the terminals and the stationary and moving parts presents problems due to the different metals and surface finishes. A stable connection with not more than 0.0005 ohms resistance is generally required. At the same time, the parts must not be subject to galvanic or normal corrosion due to climatic conditions. Protective finishes on aluminum and magnesium alloys must be removed in order to obtain the low-resistance connection, and the completed connection must be protected against corrosion. Pure aluminum washers are used between metal combinations subject to galvanic action, such as magnesium and copper. Painting the entire connection with zinc-chromate primer or similar material provides reasonable protection.

Tinned bronze lockwashers with external teeth (*AN*-936) can be used between the terminal and part to be bonded to provide a low-resistance connection by the multiple point contacts which are thereby obtained. Some practices rely on these washers to cut through insulating surfaces, such as the coating on anodized aluminum alloys, without any other preparatory cleaning of the surface.

Electric motors, generators, and other electric devices may use the frame to carry one of the circuits to a supporting part. Both mounting surfaces must be cleaned thoroughly in order to make a low-resistance metallic contact. The edges of the mounting surfaces must be protected at assembly by zinc-chromate primer or equivalent to prevent corrosion from attaching at these unprotected points.

The radio shielding of sources emitting strong radio interference, such as an aircraft-engine ignition system, presents a connection problem which requires accurate mechanical positioning of the parts in contact and joints that are watertight. Plain flat surfaces at the joints provide openings between the bolts a few tenths of a mil wide through which radio noise leaks. A continuous electric contact completely around the joint has been found necessary to keep radio noise contained within the ignition system. This can be accomplished by cutting a square groove in one joint surface and inserting in that groove a round resilient braided wire-covered gasket When the joint is assembled the braided gasket is forced to contact the flat surfaces by the resilient material inside the braid. A second method for obtaining continuous electric contact around a joint makes use of a flat gasket consisting of wire screen impregnated in Neoprene. This gasket has been found to be less effective than the round braided gasket and leaks radio noise under certain conditions.

Figure 9. Socket used on Japanese connector

Figure 10. Disassembled German 20-circuit connector

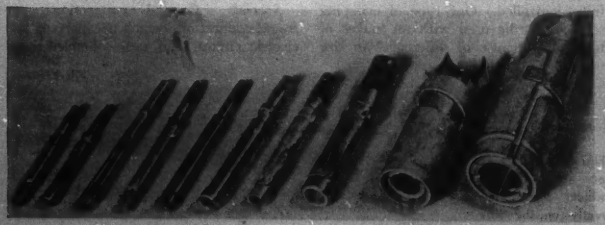

Figure 8. Typical sockets used on *AN* connectors

Quick-Disconnect-Type Connectors

When electric apparatus must be quickly and frequently disconnected, special quick disconnect types are used. Some degree of reliability is usually sacrificed to obtain the quick disconnect feature. Numerous and varied designs have been made since the beginning of the electrical industry. In an effort to standardize, the joint Army–Navy specification *AN*-9534 was issued. To supplement this specification and obtain improved designs, specification *AN-W-C*-591 was issued and is under revision at the present moment. Before discussing the merits of the *AN* connectors it might be well to consider basic designs.

Simple Direct-Pressure Type. This type consists fundamentally of two metallic parts which are held together by direct pressure to make the circuit. Generally three points of contact between the metallic surfaces carry most of the current. The contact surfaces easily may be inspected and cleaned. Dirt may come between the surfaces and prevent electric contact.

Pin and Socket Type. This type consists of a pin which slides into a socket and incorporates means for maintaining radial pressure between the pin and socket. The pin can be inspected and cleaned without difficulty. The socket surfaces are difficult to inspect, but they may be cleaned by special means.

In a few designs the spring pressure is obtained in the design of the pin, as for example, the "banana" pin construction shown in Figure 7. A split pin construction also has been used but is weak mechanically.

The most common types of pins and socket connections use solid pins and a socket which, by its design, applies spring

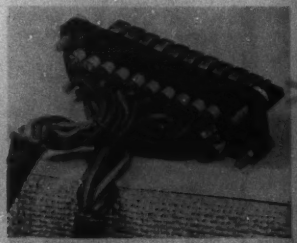

Figure 11. Rear view of German 20-circuit connector plug showing connection terminals

pressure to the pin. A wide variety of socket designs have been developed, a number of which are shown in Figure 8. A Japanese socket design is shown in Figure 9. This was a split-screw machined socket with the addition of a helical spring at the end of the socket and a *C*-shaped cylindrical spring on the body. Our experience in the operating field has shown that the use of these designs should be limited to circuits carrying less than 60 amperes. A discussion of *AN* connector design will be given later in this paper.

Sliding Contact Type. A connector design found on recent German aircraft is shown in Figures 10, 11, 12, 13, and 14. A pin is molded in the surface of the receptacle which makes a sliding contact with a flat type of spring contact on a molded plug. This design is one of the few in which the connecting surfaces easily can be inspected and cleaned. The receptable plugs are held together by a simple toggle spring arrangement, as shown, and a synthetic rubber gasket provides a tight seal to prevent water from entering.

AN Connectors

At the time this paper was written, *AN* connectors were described in specifications *AN*-9534*a* and *AN-W-C*-591. It is assumed that the reader is familiar with these specifications. Our experience in using *AN* connectors made by a wide variety of manufacturers, according to these specifications, in all types and sizes, indicates that the specifications are woefully inadequate for the insurance of obtaining satisfactory *AN* connector performance. The successful operation of *AN* connectors in the combat field has been due mainly to the choice of available connector designs and extra inspection before assembling in equipment.

One of the weakest parts of *AN* connector design from practical considerations has been in the socket. A satisfactory socket design must be one which cannot be damaged by inserting the pin at any angle which may be obtained during the process of mating the parts. It should not be damaged by test pins such as are used on circuit testing instruments.

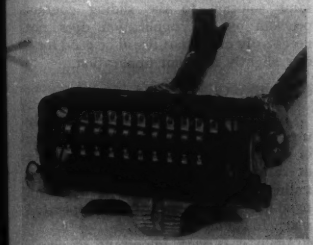

Figure 12. Plug-side view of German 20-circuit connector

Several successful designs use a solid ring at the entrance end of the socket to guide the pin into place (see Figure 8). An oversize test pin cannot be inserted in such a socket. Other successful types use auxiliary springs and bands to maintain positive contact. The sockets may be inserted in a molded phenolic insulator which limits the possible motion of the sprung sections of the socket so that they do not go beyond the elastic limit.

Adequate locking means to hold the plug and socket together are needed. Safety wire through a hole in the coupling nut to a mounting screw is very effective.

Complete 100 per cent inspection of *AN* connectors is imperative. Inspection details to be noted may be listed as follows.

Connector Shells

1. The shells shall have a good appearance with no porosity, blow holes, burrs or cracks. All sharp corners shall be broken with a $^1/_{64}$-inch radius unless otherwise specified.

2. The shell shall be of sufficient thickness so that the connector will be plugged to its mating unit in the correct position only.

Figure 13. Socket of German 20-circuit connector

3. The shell tongue shall have enough thickness and strength so that it will not break in use and will allow the connector to be plugged to its mating unit in the correct position only.

4. The shell, when spun over the phenolic insert, shall be so spun that stresses are not set up in the insert which cause the insert to break or shear.

5. Information stamped on the shell shall be correct and easily legible.

6. The snap-ring slot in the shell or in the coupling nut shall have square sides with sufficient width and depth so that the snap ring cannot pull, slide, or twist out of the slot during use of the connector. A special slot which wedges the snap ring against the coupling nut when the nut is tightened has been found to be very effective with some designs.

7. The shell threads shall be centered properly on the shell so that they are not too deep on one side and too shallow on the opposite side. The threads shall not be broken nor contain broken-out sections, and the threads on half of the shell shall be in complete alignment with those on the other half. Burrs on the threads at the casting parting line shall be removed.

8. The threads on all connectors shall be bare, except for antiseize compound, and shall have no varnish, shellac, paint, or anodic treatment.

9. The antiseize compound on the threads shall not contain grit and shall conform to *AN* specifications.

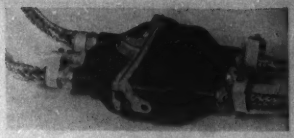

Figure 14. Assembled German 20-circuit connector

10. Flanges on the inner parts of the shell shall be square and shall project sufficiently to prevent an inner shell or phenolic insert from pushing or pulling out of the shell.

11. The connector having split shells shall be so held together by sufficient supports, and so forth, that the inner shell or phenolic insert cannot be forced out of the connector.

12. The coupling nut shall be so fastened to the shell that it can be tightened thoroughly with pliers without pulling from the shell.

13. Springs on split-shell connectors shall be of sufficient strength so they do not break nor slide out of position.

Phenolic Inserts

1. The phenolic material shall not be brittle. The pins and sockets shall not push out of the phenolic backing disk nor pull through the front of the phenolic insert during plugging and unplugging of the connector. The phenolic guide tongues, slots, edges, phenolic material between contacts, letters, shoulders, flanges, and ridges shall not fracture during connector use.

2. The phenolic material shall be an insulating material and must not contain metal dust, metal chips, or other conducting material that will allow short circuits between contacts or between contacts and shell.

3. The phenolic insert shall be so designed and built that all contacts are located properly according to *AN* drawings, and all pins of the same size must protrude the same amount inside the shell.

4. The phenolic backing disk shall have a slot fitting to a tongue in the shell, or vice versa, which will make it possible for the backing disk to be assembled in the correct position only.

5. The manufacturer of the connector shall assemble the phenolic insert of the socket-type connector with the backing disk of the socket-type connector, not with the backing disk of the pin-type connector, and vice versa. When the backing disks are incor-

Figure 15. *AN* connector after 96-hour humidity test

Figure 16. Sample Monowatt Electric Corporation *AN* snap-in-type connector

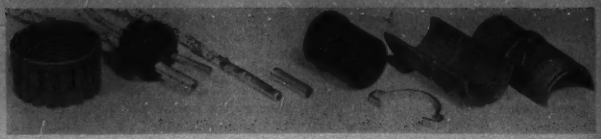

Figure 17. Sample Monowatt Electric Corporation *AN*-3106-18-5S snap-in-type connector disassembled

rectly assembled, the connector lettering is reversed.

6. The tongue on the phenolic insert shall be large and strong enough so it cannot shear or break off. This difficulty is still being experienced on size ten connectors without supporting shells on phenolic inserts.

7. The holes for the metal sockets in the phenolic inserts shall be of such size and shape that the metal socket can readily accommodate itself to the pin without the pin sliding down the outside of the socket.

8. With the connectors of the molded in pin design, the phenolic material must not shear from the pin shoulders and allow the pins to push through the sockets, for all pressures on the pins up to ten pounds.

9. The lettering at the front and rear of the pin insert must coincide with that at the front and rear of the socket insert.

10. It has been found desirable to have all the solder cups face in one direction.

11. The phenolic insert is not to push nor pull out of the connector shell during plugging or unplugging of the connector with its mating part.

Contacts

1. The pins must be of a strong durable material that will not bend nor break because of possible forcing or twisting when the connector is plugged or unplugged to its mating part.

2. The pins shall have a durable plating of sufficient thickness to prevent the formation of corrosion.

3. The pin shoulder diameter shall be large enough so that the pin will not push through the phenolic backing disk when the connector is plugged or unplugged to its mating unit.

4. The solder cup shall not break off the contact during normal use of the connector.

5. No pin is to push out through the backing disk with a pressure of ten pounds applied to it. (At General Electric Company's request the American Phenolic Corporation was set up to apply a ten-pound pressure test to each pin in the connector and mark each connector so tested with a green dot. This test increases the connector price, but the improved quality has been justified.)

6. The socket design shall be such that the sockets will not be damaged by any possible twisting or forcing when the connector is plugged to its mating unit or when test pins are inserted into the sockets. Sizes 16 and 20 sockets made by the American Phenolic Corporation, and sizes 12, 16, and 20 sockets made by the Monowatt Electric Corporation have reinforcing sleeves made of durable bronze not less than eight mils thick. (At General Electric Company's request, on and after October 23, 1943, Amphenol and Monowatt supply General Electric only with connectors that have been given an extra 100 per cent inspection at the manufacturer's plant to make certain that all small-size sockets, as mentioned previously, have reinforcing sleeves. The connector manufacturer shows this extra 100 per cent inspection by a red dot on the connector. This inspection should be applied to all banded-type sockets made by all manufacturers.)

7. The socket should be so constructed that liquid solder in the solder cup cannot leak through to the front of the socket and prevent insertion of the pin.

8. The hole in the socket should be of such shape that the pins readily slide into the sockets the first time.

9. The insert socket holes should be of such size that the sockets are free to adjust themselves to the pins when the connectors are plugged. It is preferred to have the pins fixed and the sockets floating.

When *AN* specifications are revised, it is hoped that some identifying means will be devised so that connectors according to the revised specifications can be distinguished from older types.

Corrosion protection of the *AN* connectors is not required in existing specifications. Figure 15 shows the corroded condition of an *AN* connector shell after exposure to 100 per cent humidity for 96 hours at 33 degrees centigrade. The threaded portions which were covered by antiseize compound are in perfect condition. In tropical and salt-water service, connector shells, pins, and sockets must be coated with a protective grease, for example, lanolin, to insure continued operation. This results in a very messy condition, as dust and dirt is picked up on the grease.

A new *AN* connector design with provision for safety wiring the hold nut and other advantageous features is shown in Figures 16 and 17. Connections may be made between the pins and wire by crimping, soldering, or both. Holes in the crimped tube opposite the crimp permit inspection of the crimping. The design of the insulating parts gives greater creepage distances and mechanical support to the wires without the use of insulating sleeving.

Under desert conditions, dust in the coupling nuts on *AN* connectors causes the threads to jam. The German connector design shown in Figures 10 through 14 is not affected by dust and can be disconnected quickly under any conditions. It is hoped that this advantageous characteristic may be incorporated in a future *AN* design.

Sliding Connections

The design of sliding connections is an uncompleted art. The sliding connection may be on a resistor, a commutator, or a slip ring. The choice of materials and design is controlled by many factors and variables which are not thoroughly understood. With their use on aircraft, the additional effect of high altitudes must not be overlooked. Not so long ago we were astonished when our ordinarily good carbon brushes wore out on commutators in a matter of ten minutes or less. A great deal of research effort has been required to overcome this difficulty. Today designs can be made which will operate under such conditions. The details naturally cannot be discussed because of wartime restrictions.

It is safe to say, however, that each new application must be tested thoroughly under all operating conditions. The same solution to the sliding contact problem on one application does not necessarily mean that it will be good for a new slightly different application.

Operating Connections

Operating connections are normally used for control purposes. They make or break circuits carrying electric power at various voltages and direct or alternating load currents. They range from hand-operated switches to cam-operated magneto contacts.

Again it is very important to check operating connections with the exact loading conditions under which operation

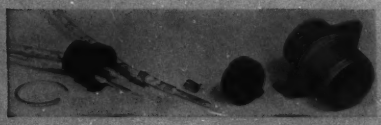

Figure 18. Sample Monowatt Electric Corporation *AN*-3106-18-5*P* snap-in-type connector disassembled

Solenoid-Operated Control Valves

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THE presentation of a paper on electric aircraft apparatus by manufacturers of hydraulic control equipment is very likely to lead to a discussion[1,5] of the relative advantages and disadvantages of hydraulic and electric systems for accessory actuation. Let us evade this controversy for the present by stating that the writers are not advocating either an all-electric or all-hydraulic system but are describing a type of device that makes possible the utilization of some of the best features of both forms of power.

It commonly is conceded that one of the strong points of electric systems is the relative lightness, cheapness, and flexibility of electric wiring over hydraulic plumbing. This is particularly true when it is required to transmit only very small power. Consequently, a system that substitutes low-energy-level electric wiring for high-energy-level hydraulic plumbing would seem to offer advantages in cost and weight for some applications, especially in the larger more advanced airplanes. For example, it has been estimated[2] that for a multiengined airplane with a hydraulic pump on each engine the use of electric remotely operated valves for controlling wing flaps reduces the length and weight of plumbing to less than one half that required for an all-hydraulic installation with direct cockpit valve control.

An additional advantage offered by this electrohydraulic system is that it makes it possible to eliminate high-potential wiring and high-pressure plumbing from the cockpit and other critical areas, thus giving a safer and cleaner installation.

Obviously, the device that makes this electrohydraulic system practicable is the remotely controlled electrically operated hydraulic valve.

General Design

The general design requirements for these electromechanical control devices are about the same as for other similar aircraft components in that they must incorporate:

1. Utmost reliability.
2. Absolute minimum weight consistent with other requirements.
3. Operation over an extremely wide range of ambient temperatures and pressures.
4. Resistance to vibration.
5. Adaptation for use in the standard aircraft electric and hydraulic systems.
6. Auxiliary means of manual operation for use in case of electric power failure.

This last requirement is not always necessary.

In designing one of these control devices the first step is to decide which of the several types of electromechanical drivers and hydraulic valves is to be used. The most commonly used drivers are electric motors, electrically heated vapor-pressure motors, and electromagnetic solenoids. Similarly, the usual valve types are the well-known slide, disk and poppet.

Various combinations of these drivers and valves have been proposed for specific purposes, but the writers believe that the combination that promises to fulfill most completely the requirements for the greatest number of applications is the electromagnetic solenoid driver applied to the piston poppet-type valve. This combination has the advantages of the simplicity and rapidity of operation (less than $^1/_{20}$ second) of the solenoid and the low fluid leakage and low operating power of the poppet-type valve. These characteristics are conducive to obtaining the lightest and most universal device.

In contrast, electric motors geared to valves as drivers are characterized by relative complexity, difficulty of obtaining manual operation, high weight for low-force valves but relatively low weight for high-force valves, and an intermediate operating time of from one to several seconds. Vapor-pressure devices are inherently simple and light but slow, requiring from approximately $^1/_2$ minute to several minutes to operate, and are likely to be more vulnerable than other devices. They are also difficult to accommodate to wide temperature and pressure ranges. Similarly, slide valves usually have greater fluid leakage than other types so that they are suitable only for hydraulic systems designed especially for their use. Disk-type valves, although simple and reliable, usually require relatively high rotary operating forces which make them suitable for adaptation to geared electric-motor drive but not solenoid actuation.

This discussion will be limited to the 24-volt d-c system, since that is the one in most general use at present.

Valve Design

Hydraulic valves are rated according to the volume of fluid that they will pass in unit time with a certain permitted pressure drop. This rated flow and the

is required. Equivalent circuits often are misleading in action.

With the increased use of electric equipment on aircraft, relay contacts have been designed to carry currents in the order of thousands of d-c amperes at 24 to 30 volts. Operating contacts for 400-cycle a-c circuits at 208 volts are under development.

Conclusions

The vital importance of electric connections on aircraft is not generally appreciated by people accustomed only to the connections on home appliances. A poor connection on an electric toaster blows a quickly replaceable five-cent fuse, and the lady of the house has to endure the hardship of eating untoasted bread until the handy man makes a repair. One poor connection on an aircraft may effect the lives of many people and cause damage in the order of hundreds of thousands of dollars.

An engineer or production man may be proud to have failures due to poor electric connections on home appliances reduced to one per cent. But, if this percentage were allowed on each of the types of electric equipment on an airplane, would he be willing to fly in the plane?

For successful modern aircraft operation, electric connections must be engineered carefully, well constructed with the proper materials, 100 per cent inspected, properly applied, and properly serviced.

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Paper 44-242, recommended by the AIEE committee on air transportation for presentation at the AIEE Los Angeles technical meeting, Los Angeles, Calif., August 29–September 1, 1944. Manuscript submitted April 21, 1944; made available for printing July 21, 1944.

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The authors acknowledge the assistance of O. R. Broberg of Adel Precision Products Corporation who did much of the preliminary work on this project.

design of the valve are the important factors that determine the force and displacement necessary to operate the valve. Two general valve designs are diagrammed in Figures 1 and 2. Cutaway illustrations of practical embodiments of the same designs are given in Figures 3 and 4.

The valve of Figures 1 and 3 is unbalanced; that is, the fluid pressure is effective on the inlet face of the poppet so that the operating force is the sum of

1. The seal frictions.
2. The product of the fluid pressure and the effective poppet area.
3. The force of the return spring.

In the partly balanced valves of Figures 2 and 4 most of the force caused by the hydraulic pressure acting on the poppet face is neutralized by reducing the effective area. This has the tremendous advantage of reducing the valve operating force as is shown by Figure 6 but the considerable disadvantage of making the manufacture more difficult and costly.

The curves of Figure 6 give the operating forces required to crack and to hold open both balanced and unbalanced poppets. These curves apply to 0.266-inch diameter poppets for three-gallon-per-minute service. The values of operating force are only approximate, since they depend to a considerable extent upon

1. Detail design.
2. Manufacturing tolerances.
3. Types of seals.
4. In the case of the partly balanced valves, upon the degree of balance that can be obtained and still maintain the fluid leakage below the rated values set forth in government specifications.

The curves will serve, however, to show the considerable savings in driver work that is made possible by using the balanced-poppet principle.

When it is considered that approximately three-quarters of the weight of an unbalanced solenoid valve is driver weight, the added difficulty of manufacture involved in the partially balanced valve is entirely justified. Also, the trend is toward higher system pressures with correspondingly higher valve operating forces which enhances the value of balanced valves.

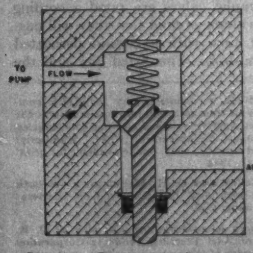

Figure 1. Diagram of unbalanced valve

This generalization in favor of partly balanced valves falls down for very small sizes. Figure 5 illustrates a cutaway model of a small shut-off valve originally intended for controlling the flow of anti-icing fluid. In this case the parts are too small and the operating pressure is too low to make a balanced construction practical. The savings of perhaps one ounce of weight out of five ounces would not be sufficient to justify the considerable added complication.

Solenoid Design

When the designer comes to the solenoid, he is in a position to take advantage of the low operating force and short travel distance that has been designed into the valve.

It would be out of place to include a detailed account of solenoid design in this paper, since this subject has been covered comprehensively in many previous publications.[3,4] Obviously, the design of solenoids for aircraft will follow the same

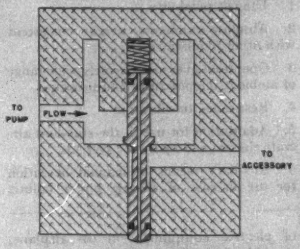

Figure 2. Diagram of balanced valve

principles incorporated in other electromagnetic devices with the exception that since weight is so very important even greater efforts than usual must be made to utilize all materials to the best advantage.

Some of the major airlines have published statements giving a dollar cost to the weight of air-borne equipment in revenue lost in diverted pay load during the life of a commercial passenger or freight airplane. This figure averages several hundred dollars per pound for such airplanes. A similar figure for military aircraft would be impossible to calculate because of the intangible considerations involved, but on the basis alone of the lower total plane mileage for military craft compared to commercial planes, it should be several thousand dollars per pound. This cost of weight contrasts to the direct cost of weight of from four to 30 cents a pound for the materials used in usual industrial electrical equipment. Accordingly, the efforts of designers of solenoid valves and similar air-borne

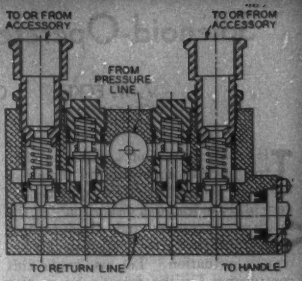

Figure 3. Section of manually operated unbalanced valve

equipment to reduce weight to the very minimum must be multiplied in proportion.

Magnetic-circuit calculations indicate that the common iron-clad cylindrical solenoid is best adapted for this purpose. This shape also has the advantages of mechanical ruggedness, manufacturing simplicity, and relative invulnerability.

Besides the increased importance of weight there are two other design considerations which differ sufficiently from usual practice to be worth mentioning:

1. Valve operation is usually intermittent, most valves being used only once or twice for a minute or two during a flight.

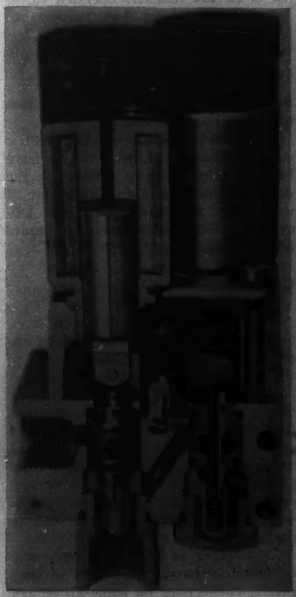

Figure 4. Cutaway model of partly balanced valve

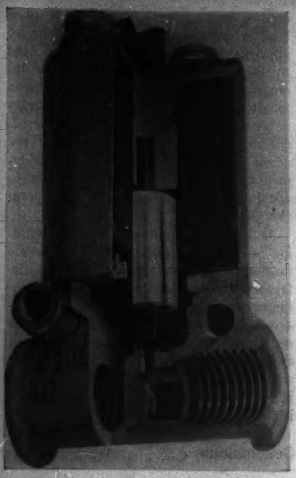

Figure 5. Cutaway model of shutoff valve

2. The expected life of this type of equipment is 20,000 operations or only a fraction of that expected of most industrial equipment. Also, electric power for the amounts and times involved is of little importance.

These considerations change the accent of the design.

One effect of these design considerations is that magnetic circuits are usually operated completely saturated. This along with the fact that the structures are small makes the problem of assuming leakage factors very difficult. As an example, a small solenoid similar to the one used on the valve of Figure 5 had nearly the same force–displacement curve without the outer iron shell as with it. This unit had been calculated carefully, but the error in assuming the leakage coefficients was so great that the outer shell had little magnetic value and, except for mechanical reasons, constituted nearly useless weight.

The engineer's first thought when confronted with the weight–duty cycle requirements along with an expected life of only 100 hours is to operate at higher than usual temperatures. Solenoids have been made using asbestos- and glass-insulated wire for operation at temperatures over 300 degrees Fahrenheit. Unfortunately, the temperature coefficient of resistance of copper is sufficiently high that the force is lowered as indicated by Figure 7 which is for an experimental glass-insulated solenoid at 0.125-inch plunger gap. When it is compared to the force–displacement curve 3 of Figure 8 for two poppets, it will be seen that a single poppet valve will operate when the solenoid is cold, will remain open for two or three minutes, and then will close automatically. After this time the valve will be entirely inoperative until it has cooled to approximately normal temperature.

Although this performance conforms with the normal duty cycle, it does not satisfy aircraft requirements in that the valve accidentally may be left in the circuit until hot in which case it will not operate if required to do so. One solution to this difficulty is to limit the temperature with a thermostatic overload switch such as is sometimes used on electric motors. A performance curve for a solenoid equipped with a thermostat switch set to open at 250 degrees Fahrenheit and reclose at 175 degrees Fahrenheit is given in Figure 9. This solenoid would operate the valve just during the time interval that the circuit was closed; during approximately 70 per cent of the

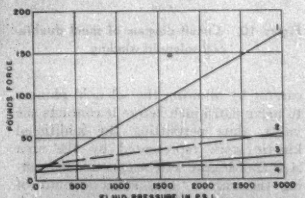

Figure 6. Hydraulic-valve-poppet operating-force curves for three-gallon-per-minute capacity (0.065-inch poppet travel)

Curve 1—Unbalanced poppet cracking force
Curve 2—Unbalanced poppet holding force
Curve 3—Balanced poppet cracking force
Curve 4—Balanced poppet holding force

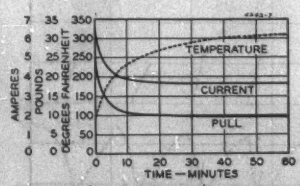

Figure 7. Solenoid force–time–temperature curves

time it would be inoperative. This probably would be satisfactory for many applications, if a better arrangement were not available.

For optimum design of the unit, the valve-operating and solenoid forces should be matched as closely as possible. This may be accomplished at least roughly by:

1. Choosing the most suitable configuration of magnetic circuit.
2. Using a double-coil winding.
3. Combinations of these two principles.

For instance, referring to Figure 8, the valve force curve 3 can be matched more closely to a solenoid curve if a high ampere-turn winding is used to give the force curve 1 with the iron circuit designed to saturate at E. At point F on the solenoid curve, the low resistance coil is switched out and a high resistance coil substituted. In contrast, a normal unsaturated solenoid designed to give adequate force at point A would have a characteristic curve similar to curve 4. The heating and weight of such a design would be prohibitive.

The double-coil arrangement uses a high-power operating coil with comparatively few turns of heavy wire connected in parallel with a high-resistance holding coil wound with a large number of turns of fine wire. A pair of contacts operated by the solenoid plunger are connected to open-circuit the pulling coil when the plunger is at the inner limit of travel. Then, when the solenoid is first energized, the circuit resistance is low because the low-resistance coil is in the circuit so that with the plunger out the force is relatively high. When the plunger travel is completed the current is reduced by open-circuiting the pulling coil. Consequently, the force and heating are reduced.

Other circuits with somewhat different characteristics are available for accomplishing this same purpose. For instance, the two coils can be connected in series with the high-resistance holding coil short-circuited for the pulling stroke and open-circuited for the holding condition. This arrangement has the advantages of slightly lower heating while holding and improved contact conditions. The disadvantage is that the necessary inrush operating current is slightly higher. The parallel coil circuit was chosen for the solenoids described because of the lower inrush current.

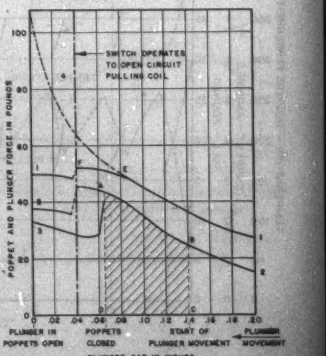

Figure 8. Poppet and solenoid force–displacement curves

Curve 1—Solenoid plunger force at 80 degrees Fahrenheit
Curve 2—Solenoid plunger force at 250 degrees Fahrenheit
Curve 3—Force for two poppets
Curve 4—Typical unsaturated solenoid plunger force at 80 degrees Fahrenheit

The solenoid designed to operate the valve of Figure 4 has a flat-ended plunger and a double coil connected as in Figure 10. This is a three-position four-connection valve using four poppets and two solenoids with each solenoid operating two poppets. The characteristic curves for 80 degrees Fahrenheit and 250 degrees Fahrenheit are given in Figure 8. The operating coil is 394 turns of number 23-gauge copper wire and the holding coil is 2,150 turns of number 32-gauge wire. The room temperature resistances are 1.90 ohms and 152 ohms respectively, giving currents of 13.7 amperes and 0.171 ampere at 26 volts. At 250 degrees Fahrenheit the force with 0.065 plunger gap is 44 pounds with approximately 46 pounds hold-in force if the operating coil is not open-circuited. With only the holding coil in the circuit the holding force is 38 pounds. With the operating coil open-circuited as in normal use but with the holding coil energized, the ultimate temperature rise after several hours is about 60 degrees Fahrenheit. If the operating coil remained in the circuit, the solenoid literally would burn up in approximately three minutes.

The solenoid furnishes a driver that will operate the partly balanced valve of Figure 4 at just 250 degrees Fahrenheit. This is 30 degrees Fahrenheit higher than the highest operating temperature of 60 degrees Fahrenheit rise over 160 degrees Fahrenheit ambient so that some reserve driver force is available. However, the works represented by the areas under the respective force–displacement curves are matched so evenly that there is inadequate reserve to insure reliable operation under adverse conditions. This is taken care of by allowing the solenoid plunger to move 0.075 inch before it contacts the valve, thus permitting the additional kinetic work represented by the area *ABCD* of Figure 8 to be effective in opening the valve. This extra amount of driver work insures satisfactory switch action and valve operation under the most adverse conditions.

One interesting suggestion regarding means of reducing solenoid weight proposes to use aluminum wire instead of copper wire. Simple calculations show that in the coil itself a weight saving of approximately one half could be effected by this means. However, when the increase in weight of the enclosing iron magnetic structure caused by the larger volume of the aluminum is considered, the net difference in the weight of the whole structure is negligible. Moreover, insulated aluminum wire is difficult to obtain which is an important consideration at present.

Another argument concerns the winding of the coil. For 24-volt d-c service random winding would be entirely satisfactory, particularly with the new high-temperature nonscuffing enamels. However, the fact that approximately ten per cent more volume is required for a random winding than for a laver winding without extra insulation increases the frame weight about five per cent which is not justifiable.

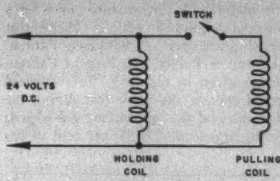

Figure 10. Circuit diagram of shunt double-coil solenoid winding

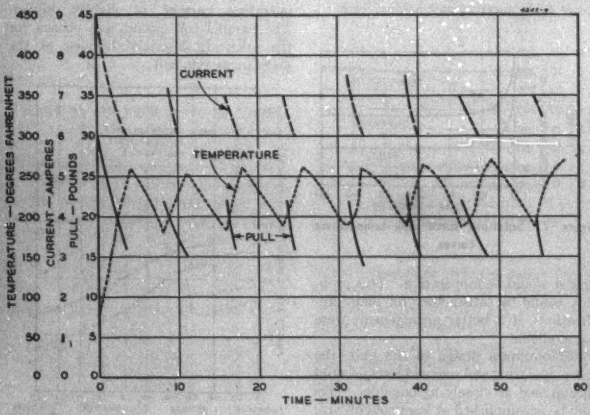

Figure 9. Force–time–temperature curves for thermostatically controlled solenoids

Conclusions

The following general conclusions may be drawn as to the use and design of electric remotely operated hydraulic valves.

1. Considerable savings in installation weight may be effected by electric remote control of hydraulic valves, particularly when the accessory to be controlled is some distance from the cockpit.

2. It may be necessary to sacrifice simplicity and low valve cost to obtain the minimum over-all weight and dollar cost.

3. The analysis indicates that solenoid valves should be designed for low operating forces and efficient electrical and mechanical elements; not so much on account of the electric power requirements but to decrease heat dissipation and, consequently, size and weight.

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A New High-Frequency Capacitor

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Synopsis: Limitations of the ordinary capacitor at high frequencies have been in part overcome by a new three-terminal feed-through capacitor having a low impedance over a wide frequency range, thus enabling improved by-passing or filtering over this wide range of frequencies.

ONE of the common uses of capacitors is by-passing high-frequency current from circuits in which direct or low-frequency current is flowing. The frequency range over which it is effective as a by-pass depends upon the relative impedance of the capacitor and the impedance across which it is connected.

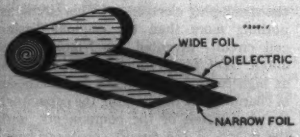

Figure 1. Isometric drawing of nearly rolled Hypass capacitor showing electrode positions

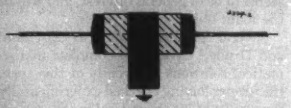

Figure 2. Completed Hypass capacitor with leads attached

The impedance of a capacitor at a given frequency is determined by its capacitance, inductance, and resistance. At low frequencies the impedance is largely determined by the capacitance, but at high frequencies and thus in most by-passing applications, lead inductance and the inherent inductance of the capacitor become the controlling factors.

Usually, capacitors for by-pass use are so chosen that series resonance occurs at the frequency where the most complete elimination of undesired high-frequency current is needed. By increasing the ratio of C to L, the frequency range over which the capacitor is effective as a by-pass can be increased. Mechanical considerations (namely, the necessity for making connections to the capacitor) and the inherent inductance of the capacitor limit the frequency range over which low impedance can be obtained by this approach.

The use of capacitors in parallel having different impedance–frequency characteristics always results in a region of high impedance where the combination becomes antiresonant. Thus, this commonly used method of by-passing over wide frequency ranges may be ineffective unless the region of antiresonance is chosen where no by-passing is needed.

A new approach to the wide-band by-passing problem is the Hypass capacitor which uses a unique design to provide an extremely broad range of low impedance extending into the ultra-high-frequency range.

Construction of the Hypass Capacitor

"Hypass" designates a three-terminal feed-through capacitor which lacks the usual resonant characteristics of ordinary capacitors. This is accomplished by operation of the capacitor as a transmission line and by a physical design which allows extremely low inductance in external connections.

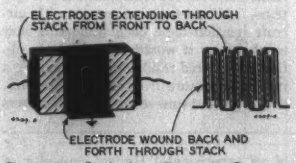

Figure 3. Stacked mica Hypass capacitor

Figure 4. Cross-section of mica Hypass capacitor

The Hypass capacitor may be constructed with the same conductor and dielectric materials as conventional types, but the internal connections to the capacitor plates and the arrangements of the plates and dielectric differ from the usual type. In its usual form the Hypass capacitor has two long foil electrodes of unequal width separated by a dielectric of intermediate width. The foils and dielectric may be wound or rolled so that the wider foil extends beyond both edges of the dielectric as shown in Figures 1 and 2. The narrow foil is centered in respect to the edges of the dielectric and connected at only one end to a terminal, usually a metal container which may be grounded. Each edge of the extending wider foil is then made essentially a unipotential surface by soldering or other means by the techniques employed in conventional "noninductive" capacitors. Leads are connected to the two resulting equipotential surfaces to carry the low-frequency or direct current through the capacitor. The current-carrying capability of the Hypass capacitor may be increased by inserting an auxiliary conductor through the capacitor without affecting adversely the frequency characteristics.

The Hypass capacitor must be inserted in a circuit just as a low-pass filter would be connected. Its usual mechanical construction lends itself to an extremely low-inductance connection to ground while inductance in the other connections enhances the filtering and thus the by-passing effect.

Many modifications of the construction outlined above are possible. Hypass capacitors have been constructed with flat dielectric sheets, such as mica, with the wider foil replaced by strips of foil extending through the stack and with the narrow foil folded back and forth pro-

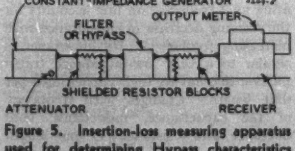

Figure 5. Insertion-loss measuring apparatus used for determining Hypass characteristics

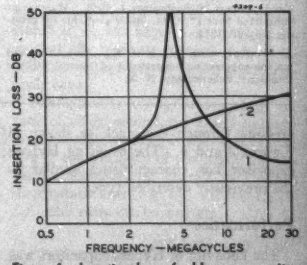

Figure 6. Insertion loss of a Hypass capacitor versus a conventional capacitor

Curve 1—Conventional 0.1 microfarad
Curve 2—Hypass 0.1 microfarad

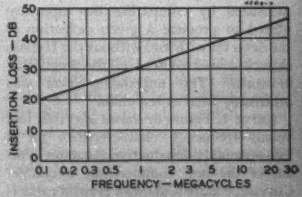

Figure 7. Insertion loss of 14.2-microfarad Hypass capacitor

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Analysis of High-Frequency Ignition Circuits

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THE modern high-voltage magnetos installed on a 2,000-horsepower aircraft engine may not resemble externally the crude induction coil used by Lenoir in 1860 to provide ignition for his gas engine. Yet, both make use of the same method to generate a transient voltage high enough to fire the spark plug. A current is first established in a primary winding surrounding a core of magnetic material and then suddenly interrupted. This interruption produces a high rate of change of flux through a secondary coil wound with a large number of turns, thus inducing a high voltage that is transmitted to the spark plug.

While their principle of operation has remained basically unchanged, the design of ignition systems has made considerable progress through the years. At the turn of the century, Simms and Bosch combined the current generator with the induction coil to make the first high-voltage magneto. Since then, new materials have become available—plastics, lightweight alloys, Alnico—and have been incorporated into improved mechanical designs to give the high-voltage magneto its present performance and reliability.

With the recent advances in aircraft-engine design, yielding higher-power outputs at higher altitudes, certain limitations of the conventional high-voltage ignition system have become of great concern to the ignition engineer. Not only is it necessary to generate and distribute higher and higher voltages at extreme altitudes, where air becomes a poor insulator, but the higher energies at the spark plug have contributed to accelerate the erosion of its electrodes and decrease its life. Fuels with high lead content, and cold running plugs, both essential prerequisites for getting more power out of a given engine, have increased the danger of spark-plug fouling, causing considerable trouble in operation.

Most of these problems have been brought under control by "fixes," and by refinements of conventional ignition systems. All persons connected with aircraft ignition have been wondering how much longer it would be possible to obtain the desired results without making a radical departure from existing systems. At the present time several manufacturers are developing new types of ignition systems that promise to get around most of the present limitations.

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Low-Voltage High-Frequency Ignition Systems

Several of the proposed systems combine high frequency with distribution at low or medium voltages, offering such outstanding advantages as:

1. Operation at very high altitudes without need for supercharging.
2. Freedom from the effects of fouling.
3. Reduced plug erosion.

Most of these systems utilize the same basic high-frequency circuit: a capacitor, charged to a predetermined voltage considerably lower than the plug voltage, is suddenly discharged through the primary winding of an oscillation transformer. The secondary winding is connected to the spark-plug electrodes. This circuit is nothing more than the original Tesla-coil circuit, invented by Nikola Tesla about 1890, for producing high voltages at high frequencies. While the methods of charging and discharging the capacitor, the disposition of the components, and the values of the circuit constants vary widely from one system to another, the analysis of the basic Tesla-coil circuit seems to be of general interest, and will be the main object of this paper.

Several scientists, such as Boynton[1] and Drude,[2] have given complete mathematical solutions of circuits of this type, the former having checked experimentally the results of his theoretical investigation. However, these results may be too complicated to be of practical use in the design of ignition systems. Boynton's solution is in the form of a Fourier series, and Drude's in the form of a definite integral. Both require considerable numerical computation to obtain the desired results.

Recently, Dr. Gabriel Kron[3] has developed a method of analysis of electrical networks which is applicable to the Tesla-coil circuit. This method is based on the principle of tensor analysis, and is extremely powerful in the solution of complex networks. Dr. Kron has applied his method to the Tesla-coil circuit, and has obtained a solution which is relatively simple and which is in a form that is readily adapted to numerical computation. The purpose of this paper is to present Dr. Kron's solution, and to show how it may be applied to the design of ignition systems.

Analysis of Tesla-Coil Circuit

The Tesla-coil circuit is shown in Fig. 1. The capacitor C_1 is charged to a voltage E, and is discharged through the primary winding of the oscillation transformer by the closing of the switch S. The secondary winding is connected to the spark plug, which is represented by the capacitor C_2. The resistance R_1 represents the primary circuit losses, and R_2 represents the secondary losses. The inductance L_1 is the primary inductance, and L_2 is the secondary inductance. The coupling between the primary and secondary windings is represented by the mutual inductance M.

Fig. 1. Tesla-coil circuit

Dr. Kron's method of analysis is based on the principle that the energy dissipated in the resistances of a network is equal to the energy supplied to the network minus the energy stored in the inductances and capacitances. Applying this principle to the circuit of Fig. 1, we have

$$\int_0^t i_1^2 R_1 \, dt + \int_0^t i_2^2 R_2 \, dt = \int_0^t e_1 i_1 \, dt - \frac{1}{2} L_1 i_1^2 - \frac{1}{2} L_2 i_2^2 - M i_1 i_2 - \frac{1}{2} C_1 e_1^2 - \frac{1}{2} C_2 e_2^2 \quad (1)$$

where i_1 and i_2 are the primary and secondary currents, and e_1 and e_2 are the voltages across the primary and secondary capacitances.

Differentiating equation (1) with respect to time, we obtain

$$i_1^2 R_1 + i_2^2 R_2 = e_1 i_1 - L_1 i_1 \frac{di_1}{dt} - L_2 i_2 \frac{di_2}{dt} - M i_1 \frac{di_2}{dt} - M i_2 \frac{di_1}{dt} - C_1 e_1 \frac{de_1}{dt} - C_2 e_2 \frac{de_2}{dt} \quad (2)$$

Since $i_1 = -C_1 \frac{de_1}{dt}$ and $i_2 = C_2 \frac{de_2}{dt}$, equation (2) may be rearranged to give

$$L_1 i_1 \frac{di_1}{dt} + L_2 i_2 \frac{di_2}{dt} + M i_1 \frac{di_2}{dt} + M i_2 \frac{di_1}{dt} + i_1^2 R_1 + i_2^2 R_2 = e_1 i_1 + e_2 i_2 \quad (3)$$

Equation (3) is the general equation for the Tesla-coil circuit. It is a nonlinear differential equation, and is not readily solved by the usual methods. However, Dr. Kron has shown that it may be solved by the method of successive approximations. The first approximation is obtained by neglecting the resistances R_1 and R_2, and the second approximation is obtained by substituting the first approximation in the resistance terms of equation (3). Higher approximations may be obtained in the same manner, but the second approximation is usually sufficiently accurate for practical purposes.

Neglecting the resistances, equation (3) becomes

$$L_1 i_1 \frac{di_1}{dt} + L_2 i_2 \frac{di_2}{dt} + M i_1 \frac{di_2}{dt} + M i_2 \frac{di_1}{dt} = e_1 i_1 + e_2 i_2 \quad (4)$$

Solving equation (4) for i_1 and i_2, we obtain the first approximation

$$i_1 = \frac{E}{L_1 \omega_1} \left(\frac{\omega_1 - \omega_2}{\omega_1 - \omega_3} \sin \omega_3 t - \frac{\omega_1 - \omega_3}{\omega_1 - \omega_2} \sin \omega_2 t \right) \quad (5)$$

$$i_2 = \frac{E}{L_2 \omega_1} \left(\frac{\omega_1 - \omega_2}{\omega_1 - \omega_3} \sin \omega_3 t - \frac{\omega_1 - \omega_3}{\omega_1 - \omega_2} \sin \omega_2 t \right) \quad (6)$$

where

$$\omega_1 = \frac{1}{1 - k^2} \left(\frac{1}{L_1 C_1} + \frac{1}{L_2 C_2} \right)$$

$$\omega_2 = \frac{1}{1 - k^2} \left(\frac{1}{L_1 C_1} + \frac{1}{L_2 C_2} - \sqrt{\left(\frac{1}{L_1 C_1} + \frac{1}{L_2 C_2} \right)^2 - \frac{4(1 - k^2)}{L_1 C_1 L_2 C_2}} \right)$$

$$\omega_3 = \frac{1}{1 - k^2} \left(\frac{1}{L_1 C_1} + \frac{1}{L_2 C_2} + \sqrt{\left(\frac{1}{L_1 C_1} + \frac{1}{L_2 C_2} \right)^2 - \frac{4(1 - k^2)}{L_1 C_1 L_2 C_2}} \right)$$

k is the coefficient of coupling, $k = \frac{M}{\sqrt{L_1 L_2}}$, and E is the initial voltage on the capacitor C_1.

Substituting equations (5) and (6) in the resistance terms of equation (3), we obtain the second approximation

$$i_1^2 R_1 + i_2^2 R_2 = \frac{E^2}{\omega_1^2} \left(\frac{R_1}{L_1^2} + \frac{R_2}{L_2^2} \right) \left(\frac{\omega_1 - \omega_2}{\omega_1 - \omega_3} \sin \omega_3 t - \frac{\omega_1 - \omega_3}{\omega_1 - \omega_2} \sin \omega_2 t \right)^2 \quad (7)$$

Equation (7) may be solved by the usual methods, and the solution is

$$i_1^2 R_1 + i_2^2 R_2 = \frac{E^2}{\omega_1^2} \left(\frac{R_1}{L_1^2} + \frac{R_2}{L_2^2} \right) \left[\frac{(\omega_1 - \omega_2)^2}{(\omega_1 - \omega_3)^2} \frac{1 - \cos 2\omega_3 t}{2} + \frac{(\omega_1 - \omega_3)^2}{(\omega_1 - \omega_2)^2} \frac{1 - \cos 2\omega_2 t}{2} - \frac{2(\omega_1 - \omega_2)(\omega_1 - \omega_3)}{(\omega_1 - \omega_3)(\omega_1 - \omega_2)} \cos (\omega_3 - \omega_2) t \right] \quad (8)$$

Equation (8) is the second approximation for the resistance terms of equation (3). Substituting equation (8) in equation (3), we obtain

$$L_1 i_1 \frac{di_1}{dt} + L_2 i_2 \frac{di_2}{dt} + M i_1 \frac{di_2}{dt} + M i_2 \frac{di_1}{dt} = e_1 i_1 + e_2 i_2 - \frac{E^2}{\omega_1^2} \left(\frac{R_1}{L_1^2} + \frac{R_2}{L_2^2} \right) \left[\frac{(\omega_1 - \omega_2)^2}{(\omega_1 - \omega_3)^2} \frac{1 - \cos 2\omega_3 t}{2} + \frac{(\omega_1 - \omega_3)^2}{(\omega_1 - \omega_2)^2} \frac{1 - \cos 2\omega_2 t}{2} - \frac{2(\omega_1 - \omega_2)(\omega_1 - \omega_3)}{(\omega_1 - \omega_3)(\omega_1 - \omega_2)} \cos (\omega_3 - \omega_2) t \right] \quad (9)$$

Solving equation (9) for i_1 and i_2, we obtain the second approximation

$$i_1 = \frac{E}{L_1 \omega_1} \left(\frac{\omega_1 - \omega_2}{\omega_1 - \omega_3} \sin \omega_3 t - \frac{\omega_1 - \omega_3}{\omega_1 - \omega_2} \sin \omega_2 t \right) + \frac{E^2}{\omega_1^2} \left(\frac{R_1}{L_1^2} + \frac{R_2}{L_2^2} \right) \left[\frac{(\omega_1 - \omega_2)^2}{(\omega_1 - \omega_3)^2} \frac{\omega_3 t - \frac{1}{2} \sin 2\omega_3 t}{2\omega_3} + \frac{(\omega_1 - \omega_3)^2}{(\omega_1 - \omega_2)^2} \frac{\omega_2 t - \frac{1}{2} \sin 2\omega_2 t}{2\omega_2} - \frac{2(\omega_1 - \omega_2)(\omega_1 - \omega_3)}{(\omega_1 - \omega_3)(\omega_1 - \omega_2)} \frac{\sin (\omega_3 - \omega_2) t}{\omega_3 - \omega_2} \right] \quad (10)$$

$$i_2 = \frac{E}{L_2 \omega_1} \left(\frac{\omega_1 - \omega_2}{\omega_1 - \omega_3} \sin \omega_3 t - \frac{\omega_1 - \omega_3}{\omega_1 - \omega_2} \sin \omega_2 t \right) + \frac{E^2}{\omega_1^2} \left(\frac{R_1}{L_1^2} + \frac{R_2}{L_2^2} \right) \left[\frac{(\omega_1 - \omega_2)^2}{(\omega_1 - \omega_3)^2} \frac{\omega_3 t - \frac{1}{2} \sin 2\omega_3 t}{2\omega_3} + \frac{(\omega_1 - \omega_3)^2}{(\omega_1 - \omega_2)^2} \frac{\omega_2 t - \frac{1}{2} \sin 2\omega_2 t}{2\omega_2} - \frac{2(\omega_1 - \omega_2)(\omega_1 - \omega_3)}{(\omega_1 - \omega_3)(\omega_1 - \omega_2)} \frac{\sin (\omega_3 - \omega_2) t}{\omega_3 - \omega_2} \right] \quad (11)$$

Equations (10) and (11) are the second approximations for the primary and secondary currents. Higher approximations may be obtained in the same manner, but the second approximation is usually sufficiently accurate for practical purposes.

Design Considerations

Equations (10) and (11) are relatively simple, and are in a form that is readily adapted to numerical computation. They may be used to determine the effects of the various circuit constants on the performance of the circuit. The following discussion will show how they may be applied to the design of ignition systems.

The first term in equations (10) and (11) is the first approximation, and the second term is the correction term. The first approximation is usually sufficiently accurate for practical purposes, and the second term may be neglected. The first approximation is a function of the sine of the frequency, and the second term is a function of the sine of twice the frequency. Thus, the second term is small compared to the first term, and may be neglected.

plete to be of much practical use to the engineer, at least in their original form. An "exact" formula, taking into account all parameters, can at best be used to calculate the performance of a device that has already been designed. The engineer, starting from scratch and faced with the problem of designing the device the best he knows how, would prefer to proceed by steps: as a starting point, a rather oversimplified theory, taking into account only the most fundamental factors, but easy to visualize, will allow him to study the basic limitations of a design, and see what they mean in terms of

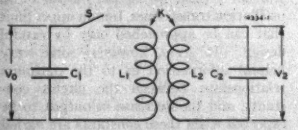

Figure 1. Basic oscillation transformer circuit

inches, materials, wire sizes, and numbers of turns. Once a preliminary layout has been made, secondary factors can be introduced one at a time as simple corrections, each one giving a closer approximation to the final result. It may be objected that such an approximate method is less accurate than an exact method. But an exact mathematical method, applied to an engineering problem, is only as good as the unavoidable assumptions on which it is based, and certainly not beyond the accuracy of the data. The main advantage of a theoretical analysis resides in its ability to break down a complex problem into its simplest elements or notions, simple enough so that each one can be visualized. This is nothing more than the method advocated by Descartes, pioneer of analysis and visualization.

Analysis of Circuit Without Losses

This section is a mathematical study of the transient generated by discharging a capacitor C_1, charged initially to a voltage V_0, through the primary winding of an oscillation transformer, the secondary winding being connected to a capacitive load C_2. Let L_1 and L_2 be the inductances of the primary and secondary circuits respectively and K the coefficient of coupling between the two windings, defined as $K=L_{12}/\sqrt{L_1L_2}$, where L_{12} is the mutual inductance between the circuits. All losses will be neglected and all circuit elements assumed to be linear (C_1, C_2, L_1, L_2, L_{12} constants). C_2, the secondary load, represents the sum of the plug capacitance, lead capacitance, and a lumped capacitance equivalent to the distributed winding capacitance. Figure 1 shows this circuit, the device for discharging the capacitor C_1 being represented schematically by a switch S.

The final purpose of the ignition system is to charge C_2 to a voltage high enough to break down the spark-plug gap, and this should be done as efficiently as possible: the circuit should be proportioned so that a large percentage of the energy initially stored in C_1, is transferred to the secondary capacitance C_2. The minimum electric power required to supply ignition to a 2,000-horsepower engine is equivalent to somewhat less than $^1/_{100}$ of a horsepower, so that, even with a very low efficiency, an ignition system would decrease the available engine power only by a negligible amount. However, if more joules must be generated per second in

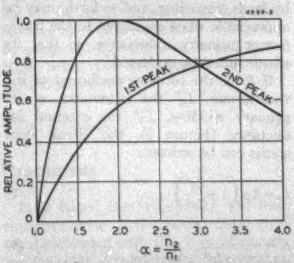

Figure 3. Effect of ratio of frequencies of components upon first and second peaks of secondary-voltage wave

the ignition system, the generating units must be bigger and heavier, and weight is at a premium on all aircraft equipment.

An ideal equivalent circuit as described in the foregoing is, of course, a pure abstraction, but its practical interest is undeniable: the values of circuit constants that will give optimum operation (highest efficiency of energy transfer) in this circuit are good approximations of the values for optimum operation in an actual case, where the output is reduced by unavoidable losses.

The differential equation of this circuit set up in the usual manner can be brought to the quadratic form:

$$(L_1L_2-L_{12}^2)p^4+\left(\frac{L_1}{C_2}+\frac{L_2}{C_1}\right)p^2+\frac{1}{C_1C_2}=0 \quad (1)$$

Regardless of boundary conditions, it shows that all natural oscillations of this circuit include components of two frequencies n_1 and n_2 determined by

$$4\pi^2n_1^2=\frac{\frac{1}{L_1C_1}+\frac{1}{L_2C_2}-\sqrt{\left(\frac{1}{L_1C_1}+\frac{1}{L_2C_2}\right)^2-4\,\frac{1-K^2}{L_1C_1L_2C_2}}}{2(1-K^2)} \quad (2)$$

$$4\pi^2n_2^2=\frac{\frac{1}{L_1C_1}+\frac{1}{L_2C_2}+\sqrt{\left(\frac{1}{L_1C_1}+\frac{1}{L_2C_2}\right)^2-4\,\frac{1-K^2}{L_1C_1L_2C_2}}}{2(1-K^2)} \quad (3)$$

These two frequencies are different from the natural frequencies of the two circuits taken separately and always frame them.

In order to determine the amplitudes and phase angles of these two components, the boundary conditions should be introduced. If it is assumed that C_1 to be charged to a voltage V_0 for $t<0$, and the switch S to be closed at $t=0$, the expression for the voltage across the capacitor C_2 is

$$v_2=\frac{L_{12}C_1V_0}{\sqrt{(L_1C_1-L_2C_2)^2+4K^2L_1C_1L_2C_2}}\times(\cos 2\pi n_1t-\cos 2\pi n_2t) \quad (4)$$

Under no conditions can v_2 be larger than

$$V_2=V_0\sqrt{\frac{C_1}{C_2}} \quad (5)$$

as, for $v_2=V_2$, all the energy initially stored in C_1 has been transferred to C_2, so that the currents through L_1 and L_2 and the voltage across C_1 are simultaneously zero.

The quantity v_2/V_2, representing the ratio of actual secondary voltage to maximum possible voltage, is thus representative of the efficiency of the circuit in converting electrostatic energy in C_1 into electrostatic energy in C_2. If $m=L_1C_1\div L_2C_2$, this ratio can be written

$$\frac{v_2}{V_2}=\frac{1}{\sqrt{1+\frac{(m-1)^2}{4K^2m}}}\times\frac{\cos 2\pi n_1t-\cos 2\pi n_2t}{2}=U\times\frac{\cos 2\pi n_1t-\cos 2\pi n_2t}{2} \quad (6)$$

The second factor,

$$\frac{\cos 2\pi n_1t-\cos 2\pi n_2t}{2}$$

represents the wave shape of the secondary voltage. Figure 2 shows this wave shape, and Figure 3 the amplitudes of the first and second peaks of this wave, plotted against the ratio of natural frequencies $\alpha=n_2/n_1$. Similar curves could be drawn for the third, fourth peaks, and so on. For $\alpha=2$, 4, 6, etc., one of these peaks will be 1, the two components being in phase and maximum at the same time.

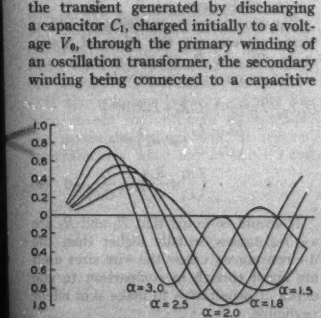

Figure 2. Theoretical wave shapes of secondary voltage

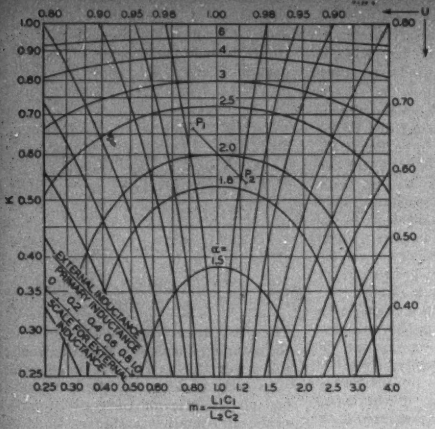

Figure 4. Chart for determination of secondary voltage

The first factor, U, is a measure of the amplitude of the secondary wave and also is at the most equal to 1.

The quantities U and α, determining the amplitude and wave shape of the secondary voltage, are functions of only two parameters, the coupling coefficient K between the circuits, and the quantity $m = L_1C_1/L_2C_2$ equal to the square of the ratio of natural frequencies of the secondary and primary circuits taken separately. These functions are represented on the chart of Figure 4.

By studying the chart, and the curves of Figure 3, the following conclusions may be reached:

1. All the energy initially in the primary capacitor will be transferred to the secondary capacitor if the primary and secondary circuits, when taken separately, have equal natural frequencies, and if the coefficient of coupling between the two circuits is 0.60.

2. These two conditions are not critical, only a slight reduction in peak secondary voltage resulting from a fairly wide departure from the ideal conditions.

The first condition gives maximum amplitude for the secondary voltage, and, combined with the second condition of 0.60 coupling coefficient, makes the higher natural frequency of the system double the lower. Maximum efficiency also could be obtained with frequency ratios of 4, 6, etc., but the corresponding coupling coefficients, 0.882, 0.956, etc., may be higher than can be practically incorporated in this type of transformer.

Effect of Primary-Lead Inductance

A certain amount of external inductance in the primary circuit, contributed by leads, capacitor, and so forth, may be appreciable when compared to the transformer primary inductance, so that its effect cannot be neglected.

If K' is the coupling coefficient of the transformer, L_1' the inductance of its primary winding, L_1'' the external inductance (Figure 5), the circuit constants can be written:

$$L_1 = L_1\left(1+\frac{L_1''}{L_1'}\right) \tag{7}$$

$$K = \frac{K'}{\sqrt{1+\frac{L_1''}{L_1'}}} \tag{8}$$

If, on the chart of Figure 4, P_1 represents the operating point of the transformer without external inductance (K' and $L_1'C_1/L_2C_2$) a simple construction makes it possible to determine the operating point P_2 for the circuit with the external inductance L_1'' in series with the primary inductance. A 45-degree line is drawn through P_1, and a distance scaled along the line corresponding to the ratio L_1''/L_1' of external to primary inductances. The scales for m and K on the chart have been chosen so that the point P_2 thus determined represents operation with external inductance.

It is interesting to notice that a fairly large percentage of external inductance can have negligible effects and that, in some cases, an increase in external inductance actually may raise the secondary voltage.

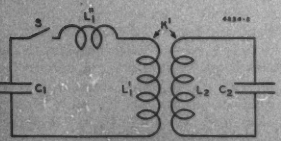

Figure 5. High-frequency ignition circuit with external inductance

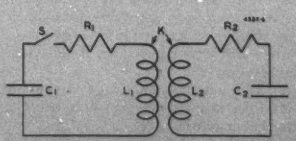

Figure 6. High-frequency ignition circuit including winding resistances

Effect of Resistance Losses

So far, only an ideal "no-loss" circuit has been considered. Such an analysis will not predict the actual output of an oscillation transformer, but an upper limit that can be approached only by careful design. It gives, however, some very helpful information as to the optimum relationships between the circuit constants, and the decrease in output to be expected when these constants are varied from their optimum values.

Many kinds of losses will cause the actual output voltage to be lower than the values given by a "no-loss" analysis:

1. Corona losses.
2. Dielectric losses.
3. Eddy-current losses in all metallic parts surrounding the high-frequency circuit, such as shielding.
4. Hysteresis losses in magnetic materials.
5. Voltage drop across the device used for discharging the capacitor.
6. Resistance losses in circuits.
7. Losses due to leakage resistance across the terminals.

Only losses due to resistance of the circuits will be briefly studied in this paper, not because all other losses can be neglected, but rather because only resistance losses lend themselves to a fairly simple mathematical analysis. While the effect of losses such as those due to eddy currents and hysteresis can be evaluated roughly by analysis, actual tests afford a simpler and more reliable way to study them.

Equation 1 can be modified by adding terms representing the effect of resistances R_1 and R_2 of the primary and secondary circuits respectively:

$$(L_1L_2-L_{12}^2)p^4+(L_1R_2+L_2R_1)p^3+\left(\frac{L_1}{C_2}+\frac{L_2}{C_1}+R_1R_2\right)p^2+\left(\frac{R_1}{C_2}+\frac{R_2}{C_1}\right)p+\frac{1}{C_1C_2}=0 \tag{9}$$

It should be noted that R_1 and R_2 are a-c resistances, usually higher than the d-c resistances, unless the wire sizes used are small enough in comparison to the depth of penetration to make skin effect negligible.

In a study of general scope such as the present, it is more desirable to express

the resistances in "per unit" values than in ohms. The amount of damping in each circuit can be represented by the dimensionless quantities:

$$\rho_1 = \frac{R_1}{2\sqrt{\frac{L_1}{C_1}}} \tag{10}$$

$$\rho_2 = \frac{R_2}{2\sqrt{\frac{L_2}{C_2}}} \tag{11}$$

ρ_1 and ρ_2 being, for each circuit taken alone, the ratio of actual resistance to the resistance for critical damping.

Equation 9 can now be written:

$$(1-K^2)p^4+2\left(\frac{\rho_1}{\sqrt{L_1C_1}}+\frac{\rho_2}{\sqrt{L_2C_2}}\right)p^3+\left(\frac{1}{L_1C_1}+\frac{1}{L_2C_2}+\frac{4\rho_1\rho_2}{\sqrt{L_1C_1L_2C_2}}\right)p^2+\frac{2}{\sqrt{L_1C_1L_2C_2}}\left(\frac{\rho_1}{\sqrt{L_2C_2}}+\frac{\rho_2}{\sqrt{L_1C_1}}\right)p+\frac{1}{L_1C_1L_2C_2}=0 \tag{12}$$

In all practical cases, the amount of damping will be small, $\rho_1 \ll 1$ and $\rho_2 \ll 1$. If the phase angles, which are small and would introduce only amplitude errors of the second order in the neighborhood of the peaks are omitted, the voltage output of the transformer can be written:

$$\frac{v_2}{V_1} = U \times \frac{\epsilon^{-\alpha_1 t}\cos 2\pi n_1 t - \epsilon^{-\alpha_2 t}\cos 2\pi n_2 t}{2} \tag{13}$$

U, n_1, and n_2 differing only by second order quantities from the values found previously in the "no-loss" case. The decrement factors, $-\alpha_1$ and $-\alpha_2$, are the real parts of the roots of equation 12.

In order further to simplify the problem, it will now be assumed that $L_1C_1 = L_2C_2$, this being a desirable condition for operation ($U=1$). The circuit damping coefficients ρ_1 and ρ_2 now enter into equation 12 only as their sum $\rho_1+\rho_2$, so that α_1 and α_2 will be functions of $\rho_1+\rho_2$. In other words, a certain per unit damping will have exactly the same effect upon the output, whether it is in the primary or the secondary circuit.

If the coupling between circuits has been chosen for optimum wave shape, the maximum voltage will be reached approximately when $\cos 2\pi n_1 t = -1$ and $\cos 2\pi n_2 t = 1$, so that v_2/V_1 will have a peak value:

$$\frac{v_{2m}}{V_1} = \frac{\epsilon^{-\alpha_1 t}+\epsilon^{-\alpha_2 t}}{2} \tag{14}$$

If all quantities beyond the first order are neglected:

$$\frac{v_{2m}}{V_1} = 1-\frac{(\alpha_1+\alpha_2)t}{2} \tag{15}$$

The sum of the roots of equation 12 is $-2(\alpha_1+\alpha_2)$, the imaginary parts canceling out as the roots form two sets of conjugate complex quantities. It is thus possible to evaluate $\alpha_1+\alpha_2$ without solving equation 12, the sum of the roots being equal to the negative value of the ratio of the coefficient of p^3 to the coefficient of p^4.

Thus, from the coefficients of equation 12:

$$\frac{v_{2m}}{V_1} = 1-\frac{(\rho_1+\rho_2)t}{2(1-K^2)\sqrt{L_1C_1}} \tag{16}$$

t, is of course the time at which the peak occurs.

The most interesting case to study is the optimum case determined in a previous section, for $m=1$ and $K=0.60$. Without losses, the maximum voltage would occur when $2\pi n_1 t = \pi$. If a small amount of damping is added, the displacement of the peaks due to this damping can be neglected, and the effect of resistance upon peak secondary voltage can be computed by equations 16 and 2, the latter being used to determine the lower natural frequency n_1.

$$\frac{v_{2m}}{V_1} = 1-3.11(\rho_1+\rho_2) \tag{17}$$

Conclusions

It is hoped that this study will help elucidate some of the fundamental concepts connected with this type of circuit. In particular, it is interesting to note that there are no critical conditions of resonance in this circuit, such as there would be if it were operated under steady-state rather than transient conditions. Also, the fact that a very high coefficient of coupling is not necessary for satisfactory operation may sound surprising at first.

The great majority of electrical problems deal with steady-state conditions, so that, whenever transient phenomena have to be considered, as in the present case, different methods of analysis and special measuring equipment are required. Fast-recurring transients usually can be studied with the aid of a cathode-ray oscilloscope, providing the extra load on the system does not change materially the transient being studied. In high-frequency ignition circuits, it is often impossible to satisfy this condition, and it may even be difficult to obtain an oscilloscope of sufficient writing speed.

There are, however, certain simple relations between the natural frequencies of oscillation of coupled circuits with low damping and the resonant frequencies of such a circuit excited by a sine-wave oscillator. For instance, if the input impedance of the circuit of Figure 1 is measured at the switch S for various frequencies, the curve of impedance versus frequency will show a maximum for a frequency approximately equal to the natural frequency of the secondary circuit taken alone and two minima corresponding to the two component frequencies of the transients studied in previous sections. The relative amplitudes of the maximum and minima give an indication of losses in the circuits. Such measurements can be made with standard equipment: a radio-frequency oscillator, a vacuum-tube voltmeter and a hot-wire ammeter. Even though they have to be taken at low flux densities, they give some interesting data that can be of great help in the test of high-frequency ignition circuits. The development of such test methods and of special measuring equipment should parallel the development of the circuits, to give a better understanding of their operation and thus guide the engineer responsible for their design.

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Inherent Overheating Protection of D-C Aircraft Motors

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Synopsis: Inherent overheating protection is undoubtedly one of the major developments in the fractional-horsepower-motor field in the last decade. Thermal protection is now advocated by some for aircraft motors, and many thermally protected motors are now in aircraft service. In this paper are reported the results of a number of laboratory tests taken on a typical aircraft motor. Tests were taken on a 1/15-horsepower 7,500-rpm d-c motor; loads ranged from locked rotor to the minimum running load sufficient to trip the thermostat. Ambient temperatures ranged from −58 to +78 degrees centigrade. Locked-rotor and running-overload temperature tests were also taken at a density altitude of 42,000 feet. Temperatures of the winding, frame, brush holders, and bearings were measured carefully under all conditions mentioned. Satisfactory protection, without premature tripping, was invariably achieved.

IN 1925, introduction of thermostatic protection to domestic flatirons revolutionized the flatiron industry. In 1928, disk-type thermostats were built into a portable-tool motor to provide built-in thermal protection. Two or three years later, thermostats were used to provide built-in overload protection for single-phase induction motors. Since that time, a quiet revolution has been taking place in the fractional horsepower motor industry, in the form of an ever-increasing use of these built-in thermal protective devices. By 1939, the Underwriters' Laboratories had become interested, and in June of that year, after conferring with electrical manufacturers making and using such devices, the Underwriters' Laboratories wrote a standard for inherent overheating protective devices; this standard was incorporated as an appendix to the Underwriters' standard for industrial control equipment.

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The author makes grateful acknowledgment to the Spencer Thermostat Company at Attleboro, Mass., who made available the use of their laboratory, where the majority of the tests reported in this paper were conducted; specifically he thanks the following for their assistance in performing these tests: L. Wood Buell, Jack Duffy, Edith Pitts, and William O'Brien. He further acknowledges valuable assistance from J. D. Miner, manager of engineering, and F. A. Heddleson, special development engineer, both of whom are at the Lima works of the Westinghouse Company.

If the present trend to thermal protection of motors continues, nearly all domestic fractional-horsepower motors will eventually be provided with inherent overheating protection.

Just because the merit and utility of inherent overheating protection for industrial fractional-horsepower motors have been indubitably established, it does not necessarily follow that similar protection is necessary, or even desirable, for aircraft motors. Requirements of motors for aircraft service differ so materially from the requirements of motors for industrial or domestic service that the worth of thermal protection for aircraft motors has to be examined in a different light. T. B. Holliday, in a recent article,[1] has pointed out a number of reasons why thermal protection of aircraft motors is desirable. Some of the reasons given by him are:

1. To prevent motor burnouts due to temporary or permanent failures of the driven device. If motor burnout is prevented, the motor itself does not have to be replaced, and as the driven device can often be repaired, a new motor—frequently not available in remote places—is not required.

2. To prevent burnouts due to improper setting or functioning of limit switches. Hydraulic systems, he points out, have relief valves which prevent damage to the system in the event of jamming, and why shouldn't electric motors be similarly protected?

3. Even turret motors should use protected motors; in the event of damage to a part of the track, it is better, Colonel Holliday argues, to save the motor, and thereby allow it to be used to traverse the good section of the track, rather than have the motor burn out completely.

4. A nonprotected landing-gear motor may burn out in an attempt to put down landing gear in which the grease has stiffened excessively, whereas a thermally protected motor may, by several starts and stops, get the gear down.

Opponents of thermal protection contend that an aircraft motor should be kept energized "to the last ounce of effort"; the "last shot" may mean the difference between life and death to the crew. It is argued that an overload device may trip at a crucial moment, whereas perhaps another second or two of operation of the motor would have saved the emergency situation.

Whatever may be the merit in these contentions, it is beyond the scope of this paper to attempt to analyze and weigh all the controversial aspects as to whether thermal protection should or should not be used for aircraft motors. Rather, the aim of this paper is to present a picture as to just how thermal protection generally functions. It was felt that such a picture could best be presented by reporting specific test data on a representative aircraft motor equipped with inherent overheating protection.

Motor-Thermostat Combinations Tested

Following are the name-plate specifications for the motor selected for this test:

Outside diameter of frame, inches	2 1/16
Volts	24
Horsepower	1/15
Rpm	7,500
Amperes at full load	3.75
Wound	Shunt
Manufacturers frame number	G-234
Open or enclosed	Open

A shunt-wound motor was chosen, because that type is more difficult to protect than a series motor.

Disk-type thermostats were used for all tests. While this device is familiar to many, a brief description of the disk principle is in order. The disk-type thermostat has as its single moving element a bimetallic disk. This disk has a dished shape, with the high-expansive side of the bimetal on the concave side of the disk at normal temperature. As the disk is heated, the bimetal on the inside of the disk tries to expand but is restrained from doing so by the concave shape of the disk, for the other side, being of nonexpansive metal, does not expand similarly; as the temperature of the disk is increased, stresses are set up tending to buckle the disk, and as soon as its

Table I. Locked-Rotor Test on the Enclosed Motor, at 26 Volts, and at an Ambient Temperature of 26 Degrees Centigrade

	Amp Just Before Thermostat Opens	On Time, Sec	Off Time, Sec	Peak Temp, Armature Winding	Temp of Front Bearing
First cycle of thermostat	21.6	4.5	3.5	68	26
Second cycle of thermostat	20.8	1.3	3.6	72	
Third cycle of thermostat	20.6	1.3	4.0	78	
Fourth cycle of thermostat	20.4	1.3	4.6	84	
Fifth cycle of thermostat	20.2	1.4	5.1	90	
Sixth cycle of thermostat	20.0	1.3	5.3	94	34
After 10 min, lapsed time	16.8	1.8	20.5	172	64
After 30 min, lapsed time	16.8	1.8	33.4	168	99
After 64 min, lapsed time	16.7	2.0	34.4	164	100

temperature has reached a certain predetermined value, the disk snaps suddenly over to the other position. When the disk cools to a definite temperature, it will snap back to its original shape. It is to be noted that this disk operates when, and only when, it reaches a certain fixed temperature, called the opening temperature. This temperature may be reached as a result of heat received from the motor, by heat generated in an auxiliary heater within the thermostat, or by both. All of the thermostats used in the tests reported herein contain an auxiliary heater, as well as the disk.

Three motor–thermostat combinations were tested:

1. Totally enclosed with a thermostat mounted on the end of the front bracket, as shown in Figure 1.

2. As a normal open motor, with a "silk-hat" type thermostat mounted on the motor frame, as shown in Figure 2.

3. As an open motor with a thermostat inside the front bracket near the commutator.

The first arrangement was chosen as representing a practical arrangement for a totally enclosed motor. While the normal horsepower rating of an open motor is reduced by enclosing, it was felt that better comparative results would be obtained if the same motor were used for all tests; in reviewing the tests, it should be borne in mind that the motor would normally be rated at less than $^1/_{15}$ horsepower when enclosed. A "silk-hat" type thermostat, as shown in Figure 2, is a normal mounting arrangement for an open motor. The third arrangement—a thermostat inside the motor—was selected for these tests because it was felt that the inside of the motor was the most logical location from a thermal standpoint. Therefore, this arrangement was tried experimentally, although it was recognized that it would not be practicable in production motors because of space considerations.

Tests on these three motor–thermostat combinations afford a good comparison of the effect of thermostat location, and illustrate the general characteristics of inherent overheating protection afforded by a disk-type thermostat.

Temperature Measurements

For locked-rotor tests which were taken first, thermocouples were soldered to the armature winding at each end; one thermocouple was tucked into an interstice in the armature end winding in order to compare temperatures with those obtained by the soldered couples. Similarly, thermocouples were also soldered to each of the field coils, and to the commutator end of a brushholder. Additional thermocouples were installed to measure temperatures of each of the bearings and of the frame. For running-load tests, the armature thermocouples had to be removed, leaving only the resistance method for determining armature temperatures after shutdown. Resistance readings were taken by a Kelvin bridge at measured intervals of time after shutdown, and a curve of resistance versus time was plotted and extrapolated back to shutdown time; temperature was computed from this resistance.

A variation of the above method, proposed by L. W. Buell, was to determine resistance while the motor was energized by the voltmeter-ammeter method. Potential-drop leads were soldered to commutator risers about 90 degrees apart; voltage drop across these leads was measured and divided by the armature current, obtaining a fictitious resistance; variation of this fictitious resistance was used as an indication of temperature.

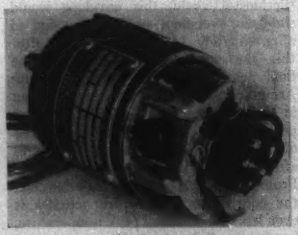


Figure 1. Small aircraft motor with thermostat mounted on the front bracket

A cap (not shown) encloses the thermostat and entire front bracket. Rating, as an open motor, is $^1/_{15}$ horsepower, 7,500 rpm

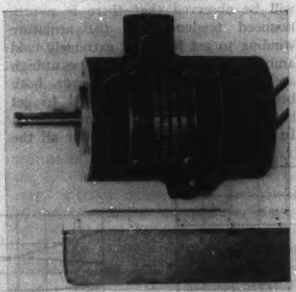


Figure 2. A $^1/_{15}$-horsepower 7,500-rpm 24-volt d-c aircraft motor with a "silk-hat" thermostat mounted on the outside of the frame

Some comparisons between temperatures by resistance and by thermocouple are of interest. Soldered thermocouples might be expected to give higher temperatures than unsoldered thermocouples, but on four locked-rotor tests, no significant and consistent difference in observed temperatures was noted. Temperatures by soldered thermocouples were compared with temperatures by resistance; of 13 locked-rotor tests, the thermocouple temperatures ranged from 2 degrees centigrade lower to 19 degrees centigrade higher, and averaged 9.5 degrees centigrade higher than the resistance temperatures. This is equivalent to saying that the temperature rise by thermocouple is approximately six per cent higher than the rise by resistance. A similar comparison was made for 56 temperature tests on fractional-horsepower motors in a previous paper; it was found that the temperature rise by unsoldered thermocouple averaged three per cent more than the temperature rise by resistances.[2]

Types of Tests Taken

Three basic types of tests on thermally protected motors are possible: locked rotor, maximum continuous load, and overload cycling. Locked-rotor tests are important because one of the major reasons for thermal protection is to prevent damage which may arise when the rotor is stalled. Maximum-continuous-load tests are taken to find out just how much load the thermally protected motor can carry without tripping the thermostat. Such a test is taken by loading the motor up to this maximum continuous load until all temperatures have stabilized, and then, increasing the load slightly, causing the thermostat to trip; immediately after tripping, all temperatures are measured. An overload-cycling test is taken by applying a load much heavier than the maximum continuous load, and allowing the motor to cycle on and off at this load value. All three basic types of tests were taken on one of the combinations listed in this paper, but the first two types were taken on all combinations.

A Typical Locked-Rotor Test

Results of one typical test showing how the thermostat cycles on and off and showing how the temperatures and motor current vary during the test are given in Table I.

At first, the thermostat cycles rapidly since the cycling time depends upon only the characteristics of the thermostat itself. In the thermostat used for these tests, the disk opens at a temperature of 147 degrees centigrade, and recloses at a temperature of 116 degrees centigrade. Therefore, during the first on period, the disk heats from 25 to 147 degrees centigrade, requiring 4.5 seconds. During first off period, the disk cools from 147 to 116, then recloses. For the second and each remaining on period, the thermostat disk has to be heated only from 116 to 147; if the motor current were

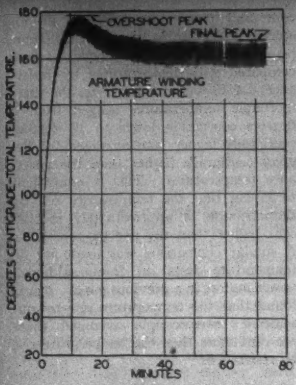


Figure 3. Temperature versus time, locked rotor

constant, this on time would be substantially the same for all remaining cycles, but as the motor current decreases because of the increase in motor temperature, the thermostat on time slowly increases, as can be noted in the table. For each reclosing cycle, the disk cools from 147 to 116, but the length of time required increases slowly as the temperature at the thermostat location increases—in this case, the front-bearing temperature.

Figure 3 shows how the temperature of the armature winding varied during the particular locked-rotor test described. This curve was drawn with a continuous one-point temperature recorder, but in the figure the time axis has been reversed so as to read from left to right. (Ordinarily, on the record of this instrument, time reads from right to left.) The first five or six temperature peaks cannot be seen on this record, since they occur too fast for the instrument to record, but subsequent peaks can be seen. If an envelope were drawn around the peak temperatures reached at the end of each thermostat cycle, this envelope would show an overshoot peak at the end of approximately 11 or 12 minutes; after this, the envelope would approach the final peak temperature asymptotically. Armature winding temperatures given in this report actually refer to the final peaks, that is, to the steady-state value of the envelope of the peak temperatures after stable conditions have been reached. From the standpoint of insulation life, the equivalent temperature actually is even less than the final peak temperature, but for simplicity the final peak temperature has been plotted in all cases.

Summary of Locked-Rotor Tests

Final results for the three motor–thermostat combinations tested are summarized and compared in Figure 4. It will be observed that there is a pronounced tendency for the armature winding to get hotter at extremely cold ambient temperatures than it does at high ambient temperatures. However, both brushholder and bearings tend to get hotter at the high ambient temperatures. In fact, there is a tendency for all the temperatures in the motor to stabilize at the same value at the high ambient temperatures. At an ambient temperature of 147 degrees centigrade (disk-opening temperature), all temperatures would be equal, because the thermostat would not allow the motor to carry any current. Of interest is the fact that similar characteristics are observed for all three motor–thermostat combinations, even including the internally mounted thermostat.

Low line voltage can often occur, and if it does, stalled-rotor conditions are more likely to occur. To determine how this condition would affect the thermal protection, a locked-rotor test was taken on the enclosed motor at 17.3 volts. Temperatures attained during this test are compared with the results of a similar test at 26 volts in the following table:

	Line Volts 26.5	17.3
Armature winding temperature:		
Overshoot peak	178	186
Final peak	176	172
Field temperature	106	109
Bearings (front)	104	102
Brushholder	105	106

No significant difference is apparent, so it is concluded that locked-rotor protection is afforded at reduced voltage, as well as at rated voltage.

It will be observed by comparing the temperatures reached with the temperature-life curves given in Figure 7 that the life of both windings and bearings under locked-rotor conditions is in excess of

Figure 4. Locked-rotor tests

⊙ Enclosed motor, thermostat on bracket
× Open motor, "silk-hat" thermostat
\+ Open motor, internal thermostat

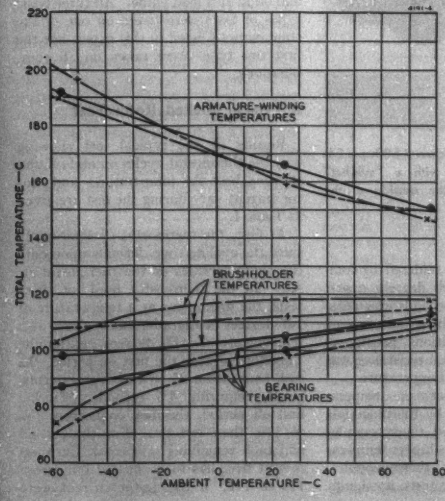
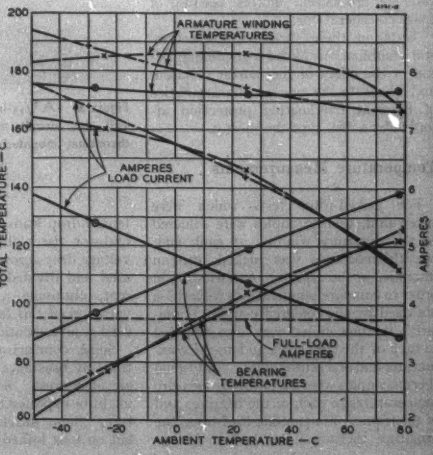


Figure 5. Maximum-continuous-load tests

⊙ Enclosed motor, thermostat on bracket
× Open motor, "silk-hat" thermostat
\+ Open motor, internal thermostat

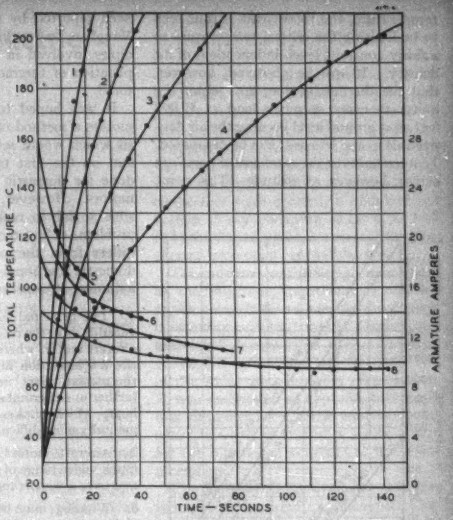


the Army's requirement of a minimum of five hours. (The corresponding life required by Underwriters' Laboratories for industrial applications is 15 days.) However, the temperatures are far in excess of those considered "safe" for industrial or domestic practice. They have been made higher deliberately, in order not to interfere with the output of the motor and because it is much more economical to operate aircraft electric equipment at high loads in spite of shortened life.

Locked-rotor heating curves for this motor were taken at four different voltages and these are plotted in Figure 6. In taking these curves the thermostat was left out of the circuit and both temperature and armature current were measured at frequent intervals. Of significant interest is the current–time curve, because torque falls off at the same rate as the current (in a series motor, it falls off faster than the current). If the load is so great the motor cannot start it cold, no useful purpose is accomplished leaving the motor on the line, for the torque steadily decreases. An unprotected motor burns out in a matter of seconds; a protected motor keeps trying intermittently for hours. If the load moves only a little with each cycle of the thermostat, the protected motor will eventually do its work while the nonprotected motor burns out and is completely useless; it is much worse than useless if it starts a fire.

Figure 6. Locked-rotor heating curves

Frame G234, 1/15-horsepower CDH aircraft motor, 24 volts, 3.75 amperes, 7,500 rpm, shunt wound, enclosed



1—Armature-winding temperature by thermocouple, at 29.9 volts
2—Armature-winding temperature by thermocouple, at 24.0 volts
3—Armature-winding temperature by thermocouple, at 19.5–19.3 volts
4—Armature-winding temperature by thermocouple, at 15.3 volts
5—Armature amperes at 29.9 volts
6—Armature amperes at 24.0 volts
7—Armature amperes at 19.5–19.3 volts
8—Armature amperes at 15.3 volts

Maximum-Continuous-Load and Overload-Cycling Tests

Maximum continuous load was defined earlier in the paper as the maximum load the motor can carry without tripping the thermostat. Experience has shown, both for industrial-type and for aircraft motors, that there is a general tendency to obtain higher winding temperatures if the motor is operated at the least possible load which will cause tripping. If the motor is operated at a load greater than the maximum continuous load, the thermostat trips in a relatively short time, but the motor temperatures are generally lower than they are at the end of a continuous run at maximum continuous load. However, if the load is maintained and if the thermostat is allowed to cycle, the final peak temperatures may be slightly higher than on a maximum-continuous-load test. Overload-cycling tests were taken only on the enclosed-motor combination, and it was found that, at or below room temperature, the armature-winding temperatures were substantially the same as for those of the maximum-continuous-load test; at higher ambient temperatures, however, there was a definite tendency to obtain lower temperatures on a cycling-overload than on a maximum-continuous-load test.

A summary of the results of maximum-continuous-load tests for all three motor-thermostat combinations is given in Figure 5. How much load the motor can carry without tripping the thermostat at various ambient temperatures is useful information, both to the motor designer and to the motor user. This is shown by the "amperes load current" curve. It is of interest that the thermostat allows the open motor to carry, even when enclosed, full-load rating up to +60 degrees centigrade. However, as an open motor, full-load rating can be carried at ambient temperatures higher than 80 degrees centigrade. It is noteworthy that the final temperatures reached by the armature winding are more or less independent of the ambient temperature, although there appears to be a slight tendency for the thermostat to cut off at lower winding temperatures when the ambient temperature is high. This trend is neither so definite nor so positive as it is in the case of locked-rotor tests. Contrariwise, it will be observed that the bearings tend to get hotter at high ambients, as might be expected; also the bearings get hotter in the enclosed motor than they do in the open motors. Limiting factor in this case is the bearing temperature of 140 degrees centigrade, which indicates a life of less than one day.

Altitude-Chamber Tests

Tests were taken in the high-altitude laboratory at Lima, Ohio, to determine what effect altitude might have upon the operation of the thermostat.[8] For tests at altitude, the pressure in the chamber was reduced, but the temperature was not, primarily for three reasons: to determine the effect of pressure alone, as the effect of ambient temperature had already been studied at ground level, some aircraft motors are operated at high ambient temperatures at altitude, and because the testing procedure was simpler and quicker. A locked-rotor test was taken, at ground level, and repeated at altitude conditions, using the same instruments, the same technique, the same personnel, and the same procedure. Similarly, a maximum-continuous-load test was taken, first at ground level, then at altitude conditions. Results of these four tests are given in Table II.

Performance of the thermostat at altitude was almost identical with operation at ground level; there was no significant difference in temperature reached, nor did the thermostat have any difficulty interrupting the locked-rotor current of 12 to 14 amperes at a density altitude of 42,000 feet.

Most interesting is the comparison of the maximum-continuous-load test at ground level with that at altitude. Armature-winding temperatures permitted by the thermostat are practically identical, and since this is the most critical

temperature, the thermostat is thus seen to be limiting the critical temperature to a fairly constant level, independent of air density. It will be observed, however, that the thermostat does not permit the motor to carry so much load at 42,000 feet as at ground level because the air density is less, and less heat can be dissipated. Temperatures of the mechanical parts are higher, however, at altitude. This point

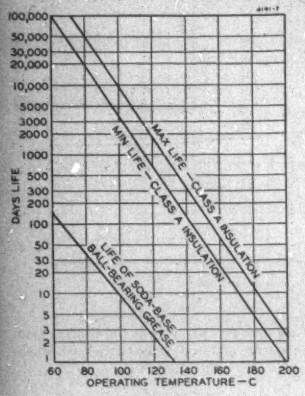


Figure 7. Effect of temperature on life of insulation and grease

Insulation life from Miner, "Insulation of Electrical Apparatus," figure 301, and grease-life information from ball-bearing manufacturers

is not difficult to understand, when it is realized that, since the total losses dissipated are less, less difference between hot-spot and frame temperatures would be expected; if hot-spot temperatures are held the same, the frame temperature will be higher with less effective ventilation. This same effect was noted for the enclosed motor in Figure 5.

Selection and Application of Thermostats

A general theory of thermal overload protection was published previously by the author.[2,3] This theory related primarily to single-phase induction motors, and showed how it was possible by means of a properly designed heater in the thermostat to make the temperature of the disk follow the temperature of the windings fairly closely. This theory was further extended quantitatively in unpublished notes to the development of mathematical formulas for selecting the right thermostat to protect any given motor properly at all loads and at all ambient temperatures. Exhaustive tests showing how effective inherent overheating protection can be in this type of motor have been reported by C. P. Potter.[4] V. G. Vaughan has outlined some of the principles involved in the selection and application of thermostats for aircraft motors.[5]

It was hoped to develop for aircraft motors a method of mathematical analysis which would select the right thermostat on the first trial the same as was done for domestic fractional-horsepower motors. However, it has not been possible so far to realize this hope for the problem of protecting aircraft motors differs from the problem of protecting domestic fractional-horsepower motors in a number of respects:

1. The principal source of heat, which is variable, is in the rotating winding of the d-c aircraft motor, whereas it is in the stator of the a-c induction motor. This means the thermostat must necessarily be removed farther in a thermal sense from the source of heat, which makes the problem fundamentally more difficult.

2. Aircraft motors must operate over a much wider range of ambient temperatures, and over a wider range of altitudes.

3. Windings must be allowed to reach much higher temperatures in order to prevent nuisance trip-outs which are many times more serious in aircraft than in domestic service.

4. Under locked-rotor conditions, the ratio of final-peak temperature to temperature at the end of the first thermostat cycle, appears to be much higher in d-c aircraft motors, than in industrial single-phase induction motors. Thus the first time of opening with locked rotor, is of less significance.

It appears that the only really satisfactory method is to determine the correct thermostat by actually running tests on a number of trial thermostats. Experience, however, is of invaluable assistance in developing simple rules-of-thumb which reduce the number of thermostats to be tried. Sometimes satisfactory results can best be obtained by making modifications in location or method of mounting the thermostat. As a specific example, when tests were first taken on the motor with the internal thermostat, it was found that considerable ventilating air was reaching the disk of the thermostat. This air tended to cool the disk, thereby permitting the motor to operate at higher temperatures on running loads; but it had no effect on locked-rotor temperatures. This difficulty was surmounted by putting a cap over the thermostat so that ventilating air could not strike the disk directly. Thus, the ratio of locked-rotor temperature to running temperature was increased without changing the thermostat itself. It is anticipated that, at other times, means may have to be taken to change this ratio of temperatures in the opposite direction. Success in applying thermostats to aircraft motors might be said to follow Edison's formula for successful invention: 2 per cent inspiration, 98 per cent perspiration.

Table II. Thermal-Overload Tests in a High-Altitude Chamber

	Ground Level	Altitude
Locked-rotor tests		
Air temp, C	+30	+33
Pressure altitude, ft		35,000
Density altitude, ft		42,000
Temp at end of test		
Armature winding by thermocouple	176.5	180.5
Shunt field by thermocouple	108.5	109.5
Brushholder by thermocouple	118	118
Bearings (front) by thermocouple	107	108
Frame by thermocouple	100.5	100.5
Thermostat case	90	93
Maximum-continuous-load tests		
Air temp, C	35	33
Pressure altitude, ft		35,000
Density altitude, ft		42,000
Maximum continuous load, amp	5.75	4.3
Temp at end of test		
Armature winding by resistance	180	186
Shunt field by thermocouple	95	126
Brushholder by thermocouple	103	130
Bearings by thermocouple	99.5	123
Frame by thermocouple	84	113
Thermostat case	80	105

Summary and Conclusions

Possibilities of inherent overheating protection for aircraft motors were investigated by taking comprehensive tests on a small aircraft motor under a wide variety of controlled conditions, including variations in: line voltage, load, ambient temperature, enclosure, thermostat location, and altitude.

Locked-rotor tests taken at ground level show that effective protection is obtained over the tested range of ambient temperatures from −58 to +78 degrees centigrade. Slightly better protection is afforded the armature winding at the upper end of this temperature range, but the bearings are better protected at the lower range, as can be seen by reference to Figure 4. A reduced-voltage test demonstrated that the protection is as effective at 17 volts as at 26 volts. Altitude-chamber tests demonstrated that the effectiveness of the protection is not impaired at 40,000 feet, also that the protective device has ample interrupting capacity at this altitude.

Running-load tests showed that effective protection is obtained over the tested range of ambient temperatures from −50 to +80 degrees centigrade. The general tendency is for the thermostat to cut the motor off the line at nearly the same armature-winding temperature, regardless of ambient temperature, although there is a tendency to limit the armature-winding temperature to a slightly lower value at the upper end of the range. However, temperatures of the bearings are invariably higher at the higher ambients, as can be seen by reference to Figure 5. When the thermally protected motor was taken from sea level

Historical Development of Electric Connectors

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Synopsis: This historical development of connectors endeavors to survey briefly the various stages of electric-connector design and the expanding applications of the uses from the earliest types for heavy-duty power applications to the smaller and more intricate fittings in aircraft, electronics, sound equipment, television, and marine applications. Because of the broad scope of the subject, the material is treated in generalizations in order to cover the history within the space limitations of this paper.

It is our belief that connector design, materials, and manufacture are keeping pace with the requirements of new electric equipment. Since the connector is essentially a component part of electric equipment, its development is affected by the requirements of new electric equipment and through adaptations for the improvement of existing equipment is increasing operating efficiencies.

THE primary role of the multicontact electric-cable connector is to disconnect and break electric circuits rapidly. It is also used as a means of switching circuits.

For wiring and servicing operations, the connector simplifies such procedure, compared, for instance, to the slow disconnection details of the screw-type terminal block. With the connector, the danger of rewiring incorrect circuits is also eliminated. The speed with which circuits can be disconnected or connected in emergencies points to another advantage as a safety factor.

In one instance, operating efficiencies of electric connectors were demonstrated in the nine hours per engine time saved in servicing and overhauling a large transport airplane.

Inasmuch as the term "plug" is often used indiscriminately to describe both receptacle and plug, it is well to define the complete connector and its two main parts. The complete connector comprises both receptacle and plug. The receptacle is that part of a complete connector which is normally "fixed," that is, rigidly attached to or an integral part of a supporting surface. The plug is that part of the complete connector which is normally removable after disengagement. Either plug or receptacle may be provided with socket or pin-contact insert assemblies. The type *AN*3101, however, is an exception to the rule.

The choice of a type letter has, for the most part, been variously adopted, depending upon the general use or even—as in the case of type *F* (Figure 1)—for the company, Fox Motion Picture Studios, for whom it was designed. Fortunately, when the Army and Navy specifications connectors were created, a standardized system of nomenclature of parts as well as types was adopted, for which the engineering profession can well be proud.

The precursor to the electric connectors as modified and improved for aircraft applications is found among those early connectors built by James H. Cannon and associates shortly after 1920. The first of these is termed the *M*1–4. It is still in use today and far from obsolescence. It was designed as type *M*, because it was designed for electric motors, 1 because it was the first of a series, and 4 for the number of contacts in the insert assembly.

Compared with the average connectors in use today in aircraft applications, Cannon type *M* (Figure 2) is oversize. Its shell, however, like aircraft connectors today, is aluminum. The inserts were fabricated of laminated phenolics, one having floating female or socket contacts with tapered bores and the mating insert having fixed split male or pin contacts which assumed the angle of the tapered bore sockets upon insertion. Even this pioneer design did not differ greatly from the aircraft connector of today.

Coupling was maintained only by the wedging action of pin and socket con-

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to 40,000 feet, the following characteristics were observed: less load-carrying ability, substantially the same armature-winding temperature, and higher temperatures of bearings. Enclosing an open motor has a similar effect.

The effectiveness of thermal protection is shown by the fact that, over the entire range of conditions tested, including the three motor-thermostat combinations, the armature-winding temperature was held between the limits of 147 and 196 degrees centigrade. Exclusive of locked-rotor tests, the armature-winding temperature was held by the thermostat, under all conditions, between the narrower limits of 166 to 186 degrees centigrade. These figures are well above the range of temperatures which are encountered in any properly applied aircraft motor under any normal conditions. Hence the thermostat will trip only when abnormal conditions are encountered. But the temperatures permitted by the thermostat are low enough to permit a life of a day or more under abnormal conditions.

In the author's opinion, the temperatures for which the thermostats were set are a reasonable compromise. Appreciably lower values might result in nuisance trip-outs, as unnecessary as they might be dangerous. Use of higher temperatures might possibly be justified on the grounds that a minimum of one day's life is unnecessary, but it should be pointed out that maximum horsepower output of a motor decreases with the temperature. Furthermore, some allowance must be made for variations in individual motors and individual thermostats. Also, there are other parts of the motor which can be damaged by excessive temperature, including: bearings, brushholders, shunts, and so forth.

Results comparable to those reported in this paper are to be expected only if skill and care are used in the application of the thermostat. But when this is done, inherent overheating protection is afforded against all abnormal operating conditions, without danger of preventing the motor from performing its normal functions. Thus motor burnouts and consequent replacement can be prevented by thermal protection.

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tacts; yet this proved satisfactory for the applications. This is in contrast to later developments which introduced types with latch-locking devices providing a quick and positive means of coupling, threaded coupling nuts, and also coupling nuts augmented with provisions for safety wire, which presented a more satisfactory means of overcoming problems of weatherproofing and vibration.

In this early type-*M* connector, floating sockets were used. This method of mounting the socket contacts has remained a fundamental standard.

When sound-motion pictures went into production in the late '20's type-*M* connectors were used for certain electric circuits, including synchronous camera motors, microphone circuits, and camera blimps, although later type-*M* connectors were exchanged for smaller and lighter fittings in many cases.

Following the type *M*1, came the *M*2, with a three-inch insert diameter having a greater number of contacts. Next came the *M*3 (Figure 2) with an insert diameter of $4^{9}/_{16}$ inches. Type M1 carried contacts for 30-ampere service, *M*2 for 30- and 60-ampere service, and *M*3 from 30- to 90-ampere service.

As can be readily seen, the trend to larger connectors carrying a greater number of circuits in the same general design reached a point of diminishing utility. For example, the *M*3-26 (Figure 3) plug weighed $3^{1}/_{2}$ pounds. Compare this to an *AN* plug with 30 similar contacts weighing 0.336 pound. Variations of the *M* fittings were made, having up to 30 circuits.

However, it was also apparent that the smaller connector would have a wider variety of uses. This opportunity came in 1925, when a certain connector failed to meet a motion-picture sound studio's requirements both in socket design and

Figure 1. Type-*F* plug, straight-type, with pin insert assembly and cable clamp

delivery. An emergency had arisen. However, within a few days, samples were submitted embodying a newly designed socket machined from one-quarter-inch-square brass rod, having a leaf-type contact spring riveted to one side. Cable clamps were cast onto the brass end bell. Pins were pressed into laminated phenolic inserts. Sockets used were the standard full-floating type, which also enabled the sound engineers to avoid variations in contact resistance when the fittings were moved during recording.

Thus the type-*F* Cannon connector was conceived and born, with *F* for Fox Motion Picture Studios as a constant reminder of its motive origin. The *F* type proved successful and soon became the standard connector, not only for cinema sound-production equipment, but in many radio stations.

Actually, it was this type *F* that caught the interest of aircraft and airline engineers, beginning the aircraft phase of connectors. But, in the meantime, to be chronologically correct, the type *P* (Figure 3)—*P* for Paramount Studios—was designed, representing the trend toward smaller and more compact connectors. Type *P* had an insert diameter of one inch, a latch-coupling device, a die-cast shell, and molded inserts. These represented definite advances in design and materials which were reflected in connectors built a number of years later. Type *O*—O for oval design—soon followed type *P* and was designed for the inductor-type microphone.

All during these years the aircraft industry was growing, if slowly, and, with the increasing circuits and new service problems, connectors were soon or later bound to be used. The opportunity

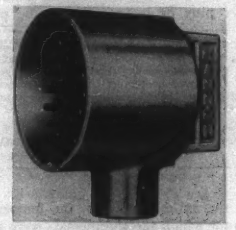

Figure 2. Type-M3 90-degree-angle plug, with pin insert assembly

came one day late in 1932, when James H. Cannon showed a type-*F* connector to Warren Boughton, chief electrical engineer at Douglas Aircraft Company. At this time the *DC*-1 transport ship was in the blueprint stage. Mr. Boughton believed the type-*F* connector to be adaptable to aircraft requirements. Modifications subsequently were made and accepted. Transcontinental and Western Airlines specified it for use on their new airliners to be built by the Douglas Company.

The shell material of the *F* was changed from brass to aluminum, and type *F* became *AF* (Figure 4), *A* for aircraft, and the transition from sound equipment to aircraft was complete.

For use on the type *DC*-2 transport airplane in 1933, the cable clamp entrance on the *AF* connector was eliminated, and threads were put on the cable entrance of the shells to permit the use of flexible conduit. At the same time, requirements for additional contacts made it necessary to increase the number of insert arrangements.

The use of connectors increased the safety of aircraft electric circuits and cut down servicing time by many hours, and maintenance of electric circuits was greatly simplified, resulting in labor and time-saving factors. Although numerous developments have been made since that time, these three basic features of electric connectors seldom have varied and remain essentially the same today.

Following closely upon the *AF*, type *FM* (Figure 5) was developed, having a two-inch insert diameter to meet new requirements of aircraft and the concomitant need for more contacts and greater clearance between contacts. Otherwise, the *FM* was identical to the type *F*.

Figure 3. Type-P straight cord plug, with socket insert assembly, lower right. Type-P 90-degree-angle plug shown upper left engaged in type-P two-gang panel receptacle, flush-mounting, with pin insert assemblies

The continued demand for lighter and smaller connectors used in many applications such as aircraft fire-wall connections, radio transmitters, radio control panels, tachometers, resistance thermometers, gauge indicators, remote-control thermostats, pumps, various small motors, lights, and governors, resulted in the design of the type *K*, (Figure 6), the first connector series to be designed specifically for airborne equipment. The *K* series was built in eight basic shell sizes, with inserts containing from one to 100 contacts, and in a wide variety of contact sizes, voltage spacings, and amperage ratings. Type *K* represented a marked achievement in the design of electric connectors.

In the type *K*, socket contacts were made from round rod stock, as this type of construction provided a means of grouping more contacts within a limited insert area. Thus, mechanical spacing was reduced with no loss in creepage between contacts. The insulators were fabricated out of sheet phenolic, although

during the later development of type *K* molded insulators were used in conjunction with the fabricated type. Shell parts were made of aluminum alloy. Coupling was maintained with a coupling nut having a modified Acme thread, which provided a rapid means of coupling. An exception was the large *AK* size (Figure 6) which used the conventional *NF* thread. On the *AK*, the screw-jack action of the coupling nut was necessary to engage and disengage the fitting, because of the force required to engage and disengage fittings having a large number of contacts.

The smallest type *K* has an insert diameter of five-eighths inch, and the largest, $2\frac{1}{4}$ inches. Type-*K* shell styles

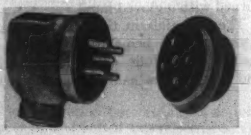

Figure 4. Type-*AF* 90-degree-angle plug, with pin insert assembly, and opposite, type-*AF* wall-mounting receptacle, with socket insert assembly

were available in straight, 90-degree-angle, and wall-mounting types, including a special end bell having an integral clamp if required, and accessory fittings included dust caps, dummy, or stowage receptacles, and 90-degree-angle and straight junction shells. Cable entries in the *K* are of two types, taper and straight, with three available conduit threads in several sizes: *B* for Breeze-type thread, once standard for the United States Navy, *AC* for Air Corps and the new *AN* standard.

In 1936, a move to merge the divergent specifications of the Army Air Forces and the Navy Bureau of Aeronautics into one standard was begun for the sake of efficiency and economy. This new Army–Navy specifications on electric connectors was known as *AN*-9534. Since that time, a second specification, *AN-W-C*-591, has been drawn up, with an amended specification pending. The original *AN*-9534, issued November 1, 1939, covered 18 basic shell sizes in five different types: *AN*3100 (wall-mounting), *AN*3102 (box-mounting), *AN*3106 (straight), *AN*3108 (90-degree-angle), and type *RC* (integral-mounting). At that time 53 insert arrangements were available, whereas the total now exceeds 250.

For the type *AN*3102, see Figure 7 and Figure 8; type *AN*3106, Figure 9 and Figure 10; type *AN*3108, Figure 11.

It should be noted that type-*RC* integral mounting was intended for use where the shell of the receptacle is made an integral part of the electric equipment housing.

AN-9534 Specification:*

A. Plug and receptacle, with the exception of receptacle type *RC*, were to be interchangeable between their respective plug and receptacle shells, which applied to each manufacturer's own product and did not require the inserts made by one manufacturer to fit any other manufacturer's plug or receptacle shells.

B. Contacts were made from material of high-grade conductivity. Contacts silver-plated, except those made of thermocouple material.

C. Interior face of solder cups completely tinned.

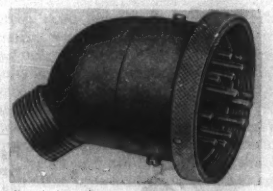

Figure 5. Type-*FM* 45-degree-angle plug, with pin insert assembly

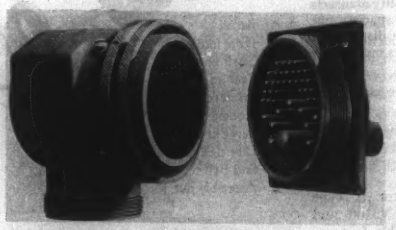

Figure 6. Type *K* (*AK* shell size shown with *NF* thread on coupling nut)

Left, 90-degree-angle plug with socket insert assembly. Right, wall-mounting receptacle with pin insert assembly

D. Pin and socket contacts sizes 0, 4, and 8 were designed so that they could be readily removed from their inserts for soldering to conductors and easily assembled after the soldered connection was made.

E. Potential millivolt drop not to exceed 7 to 12 on contact sizes 20 to 0, with a range of current from 5 to 200 amperes, between each contact and other contacts and shell.

F. Separating force ranged from two pounds on size—20 contact to 20 pounds on number—0 contact.

G. Four service ratings—instrument (peak voltage of 70); 24 volts (peak, 100); 110 volts (peak, 350); and 500 volts (peak, 1,000).

H. Allowable creepage was based on service for which insert was designed; namely, $\frac{1}{16}$ inch on instrument, $\frac{1}{8}$ inch on 24 volts, $\frac{3}{16}$ inch on 110 volts, and $\frac{1}{4}$ inch on 500 volts.

I. Three positioning inserts made possible three distinct polarizations, numbers 1, 2, and 3, by rotating insert in shell. Thus, three identical inserts placed side by side would have distinctly different polarization.

J. Plugs were of such construction that it would be possible to install a plug on both ends of a conduit assembly without excessive slack in the conductors within the conduit. To meet these requirements, Cannon designed an end bell which was split in half so that both halves could be removed to provide ample space for servicing.

K. Shells and receptacle fittings were made of high-grade aluminum alloys.

L. Phenolic materials were used in insert assemblies.

The amended *AN*9534a specification, issued in December 1941, superseding *AN*9534, contained the following main changes:

A. Requirements for three positions of inserts were removed, and only position 1 was retained.

B. Original specifications provided for the maximum operating voltages for direct current and alternating current under the various service designations. Under the amended specification *AN*9534*a*, the a-c maximum was removed and the d-c table retained. However, reference to alternating current or direct current was removed.

C. The number of insert arrangements was increased to 87.

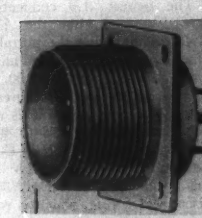

Figure 7. Type-*AN* 3102 receptacle with pin insert assembly

D. Type-*RC* receptacle was assigned drawing number *AND*10066.

The new specification *AN-W-C*-591, issued in December 1941, which became effective June 1942, carried the bulk of *AN*9534a as well as *AN*9534, with the following changes:

A. Deletion of markings of instrument, 24 volt, 110 volt, and 500 volt, from the face of the insulator. Instrument, 24 volt,

* Adapted from the Army–Navy specifications.

and 110 volt were grouped under service *A*, 500 volt under service *B*, and such high voltages as 14,000 under service *C*.

B. Since military aircraft, in particular, was seeking higher altitudes, effective creepage distances were increased. Service *A* with a peak voltage of 200 required one-eighth-inch minimum creepage distance; service *B* with a peak voltage of 750, $^{5}/_{16}$ inch; and service *C*, 14,000 volts, one inch. To maintain the interchangeability of inserts and also retain the mechanical spacing, but increase the effective creepage distance, it was necessary to design barriers on the face of the inserts.

C. Shell sizes 44 and 48 were eliminated from the new specification.

D. Type-*RC* integral mounting was issued a number series for shell sizes, *AND*10425 to *AND*10436.

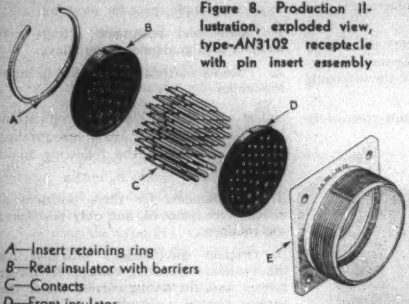

Figure 8. Production illustration, exploded view, type-*AN*3102 receptacle with pin insert assembly

A—Insert retaining ring
B—Rear insulator with barriers
C—Contacts
D—Front insulator
E—Shell

The newest *AN* connector is type *AN*3101 which, like the *AN*3106 and *AN*3108, embodies the portable features of a plug, but is not a fixed mounting like types *AN*3102 or *AN*3100. However, type *AN*3101 has the threaded cable entry of a receptacle. This new type is being made in sizes 8*S* to 40 inclusive, under the proposed *AN-W-C-591a* specification. Another new *AN* type under this specification is the *AN*3017, quick-disconnect fitting, which is restricted to sizes 8*S* to 20.

Among other connectors which are used in one way or another on aircraft or other war material which are of considerable importance but rather specialized in application, are the type *DP* and battery connectors, both developed within the last four or five years.

The *DP* is best generally described as rectangular in shape. *DP*'s are particularly adapted to rack-mounted radio and range-finding equipment. Several *DP* types mount directly to the outside face of the chassis itself, alignment being effected by a taper in the shell and by the contact arrangement itself. Coaxial contacts for radio antennas are standard in several of the *DP* fittings. Contacts vary from 10 to 135, the largest connector in the series being type *DPL* used for special equipment by the Army Air Corps.

A notable development of the line of battery connectors, which have been in use for a number of years in engine starting and other applications, is the type numbered 11,749 and 11,751, which was developed at the request of the Air Corps to facilitate disconnection of batteries, particularly in extremely cold climates. The design formerly in use required the maintenance mechanic to loosen two small wing nuts before removing the battery, a slow and difficult process in subzero weather. During removal, the battery contacts were likely to strike the aluminum side of the air frame, creating a short circuit and consequent fire hazard, whereas this new development completely encloses the contacts. In addition, it has a handwheel for disconnection, which can easily be turned with a gloved hand.

Figure 9. Type-*AN*-3106 plug, with socket insert assembly

The materials in the insert insulators constantly are being improved to overcome high-altitude problems, humidity, and fungus growths of tropical climates, and circumstances of salt-water conditions. Research in thermoplastics, thermosetting materials, and protective coatings is going forward rapidly.

Briefly, among the other developments which are yet to be recorded in the chapters on the history of electric connectors are snap-in solderless contacts. Still other new developments not entirely out of the experimental stages include the following: connectors having a greater voltage for high cycle; special switching devices which operate engine-starting units; and waterproof designs for marine and ordnance requirements.

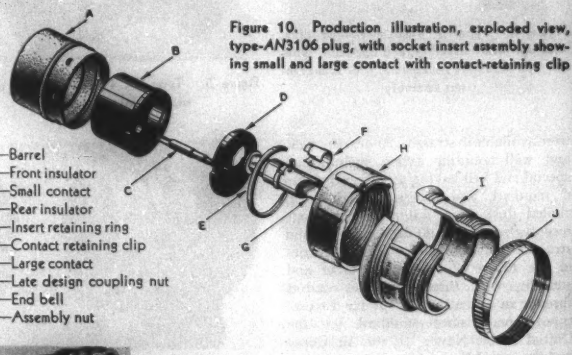

Figure 10. Production illustration, exploded view, type-*AN*3106 plug, with socket insert assembly showing small and large contact with contact-retaining clip

A—Barrel
B—Front insulator
C—Small contact
D—Rear insulator
E—Insert retaining ring
F—Contact retaining clip
G—Large contact
H—Late design coupling nut
I—End bell
J—Assembly nut

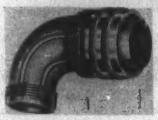

Figure 11. Type-*AN*3108 90-degree-angle plug with socket insert assembly

The Testing of Brushes for Life and Performance Under Various Altitude Conditions

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ASSOCIATE AIEE

Synopsis: This paper presents the author's experience in the testing of brushes on machines intended for high-altitude service on aircraft equipment. The procedure and range of conditions found useful in testing a wide variety of small a-c and d-c machines are outlined in detail. It is hoped that other investigators will contribute their experiences through discussions or additional papers, and that from this material there may be developed a suitable test code, supplementing the present Institute test code for d-c machines.

The only real criterion of brush performance is that of actual experience in service, since all of the infinite variety of conditions that affect brush performance cannot be anticipated under test conditions. However, carefully conducted tests over a range of specified conditions do provide a good basis for brush selection and greatly expedite the final choice for the best over-all performance. For this reason, and because it will be helpful to investigators in comparing their results, it is hoped that the proposed brush test code may be undertaken in the near future.

IN brush-life testing on machines, many confusing, conflicting, and variable results are observed even under normal atmospheric conditions. These uncertainties are increased greatly in high-altitude tests. Many tests by various laboratories have shown that most brushes are affected greatly by the changes in humidity, oxygen content, or pressure of the surrounding air. It is a common experience for carbon brushes to wear away at extreme rates up to half an inch or more per hour when run on high-speed commutators or slip rings in extremely dry atmospheres.

This rapid wear can be inhibited by a great variety of contaminants if present in small quantities in the air, in the brush, or even in the metal of the commutator. Test results therefore are likely to vary greatly unless scrupulous care is taken to exclude unwanted materials and to maintain precise control of the atmosphere.

It is not the purpose of this paper to discuss any of the methods for preventing brush wear, but simply to describe the testing procedure found useful in obtaining definite and reasonably consistent results in the measuring of brush performance. Uniform methods of conducting and reporting brush-life tests are proposed, so that wherever or by whomever tests are made, the results will be of value for record and will be truly comparable with other tests made at other times and places.

General Considerations

The primary purpose in brush testing is to determine, as nearly as possible, if satisfactory operation will be obtained in actual service. Therefore, all known conditions of loading, atmosphere vibration, and power-supply characteristics which occur in service should be duplicated as closely as is practical within the limitations of testing equipment. On many aircraft applications the ranges of load and atmospheric conditions are so extreme and duty cycles are so variable, that the establishment of adequate test cycles may require very careful study and judgment. In many cases it may be impossible to establish satisfactorily brush performance until the representative loads encountered in service are known.

Nearly all of the electrical and many of the mechanical defects which commonly occur on machines adversely affect the life and performance of the brushes. It is impossible to evaluate the brushes unless adequate measurements are taken to make sure that electrical and mechanical conditions of the machine remain substantially constant throughout the test. In order to differentiate between brush failures due to properties of the brush material and the failures induced by mechanical and electrical defects occurring in particular machines, it is necessary to make very comprehensive measurements and observations of all factors known to affect brushes.

Tests should be taken only on machines in good working condition, because the effects of many electrical and mechanical defects upon brush operation seldom can be appraised accurately. Small machines often are damaged by rough handling causing brinelled ball bearings, bent shafts, damaged or dirty commutator or collector surfaces, bad balance, bent or improperly located brush holders; all are factors which adversely affect the brushes. Where there is any possibility that careless handling has occurred, very careful mechanical inspection should be made before any tests are begun.

To predict brush life reasonably well on the basis of relatively short tests, careful study of the nature of commutator, ring, and brush wear is necessary. It appears necessary also to study the films formed on commutators and rings for evidence of any marked changes in appearance with time. The gradual formation of excessive or uneven film during several days of operation has often appeared to be the principal cause of brush failure.

The "Brush-Qualification Test Procedures" outlined in the appendix have as their purpose the determination of three fundamental factors of brush operation which are often almost equally important. These factors are: brush life, commutator life, constancy and suita-

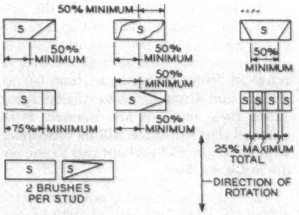

Figure 1. Views of brush face

S represents seated portion of brush

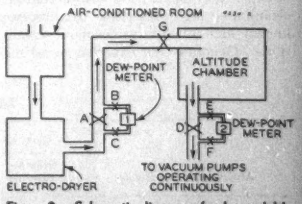

Figure 2. Schematic diagram of a dependable high-altitude chamber system

Valves *A*, *B*, *C*, and *D*, *E*, *F* are used only to produce sufficient pressure head across the dew-point meters to produce distinct meter readings. Meter 1 reads dew point of the air entering the altitude chamber. Meter 2 reads dew point of the air usually in center of altitude chamber. Throttling valve *G* is adjusted to maintain the required altitude

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The author acknowledges the assistance of E. R. Summers, General Electric Company, for preparation of uniform methods for reporting brush test results; J. F. Settle, General Electric Company, and S. W. Glass, National Carbon Company, for their contributions in the development of high-altitude test procedures.

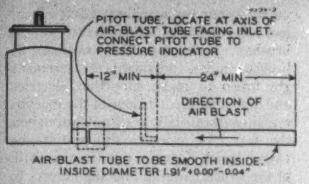

PITOT TUBE. LOCATE AT AXIS OF AIR-BLAST TUBE FACING INLET. CONNECT PITOT TUBE TO PRESSURE INDICATOR
12" MIN
24" MIN
DIRECTION OF AIR BLAST
AIR-BLAST TUBE TO BE SMOOTH INSIDE. INSIDE DIAMETER 1.91"+0.00"-0.04"

Figure 3. Typical Pitot and air-blast-tube installation for test of aircraft-engine generators

bility of machine characteristics as affected by the brushes. The use of any brush grade usually represents some compromise among these three factors. To match the brush with the machine to secure required performance characteristics is often more important than to match brush and machine to secure maximum brush life.

Types of Tests

It has been found useful to classify tests according to two general types of atmospheric conditions which are generally designated as low altitude or high altitude.

Low altitude covers the ranges of atmospheric conditions usually encountered in test departments and laboratories. The air should be relatively free from chemical, smoke, paint, and any other fumes which are known markedly to affect brush operation. It is proposed that low altitude should include the following listed range of conditions:

1. Altitude from sea level to 1,000 meters.
2. Ambient air temperature from 20 to 40 degrees centigrade.
3. Relative humidity from 20 to 90 per cent.

High altitude is defined as being any atmospheric condition above 1,000 meters in test chambers where the air pressure, dew point, ambient temperature, and air cleanliness are controlled to simulate known high-altitude atmospheric conditions. Generally our experience and the reported results of other investigators have shown that there are no marked changes in brush performance until free-air altitudes of 10,000 to 15,000 feet are exceeded. Because of these experiences and the practical need to limit variations in test conditions to a reasonable minimum, it is proposed that only four general classes of high altitude be adopted as standard. These classes are based upon the estimated atmospheric conditions encountered in or on airplanes, and are proposed to be as shown in Table I.

Classes I, II, and III of Table I are intended to apply to all totally enclosed or self-ventilated machines. Class IV may apply to either self-ventilated or rammed-air-ventilated machines located in the engine nacelles.

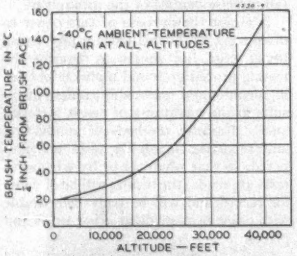


Figure 4. Brush temperature versus altitude

Many machines without adequate ventilation for cooling brushes and commutator at high altitudes soon reach critical temperatures as altitude is increased

Conclusions

The test procedures listed in the appendix have been worked out as a result of conducting some 600 tests on small a-c and d-c machines for aircraft use over a range of from six watts to four horsepower, and from 2,500 to 15,000 rpm. When these methods are followed, it is believed that brush life will be consistent within the range of perhaps two to one on duplicate machine.

It is very important, however, to note all differences and conditions which may have a bearing on brush performance, so that if later tests give different results, the reason for the difference may be traced.

In studies of brush application, the individuality of different machine designs makes over-all solutions improbable. However, it is believed that close agreement can be obtained by different observers at different times and places on the basic question, "What is a good brush for the particular application?" if the "Brush-Qualification Test Procedure" listed in the appendix is followed. It is proposed that these test procedures and "Types of Tests" should be combined suitably to form a brush test code.

The testing of brushes for life and performance involves two distinct types of measurements. These are the reasonably exact mechanical, electrical, and thermal measurements; and the relatively inexact observational measurements for which the accuracy and usefulness largely are dependent upon the observer's experience in studying brush phenomena. It does not seem likely that sufficient exact measurements can ever be made to provide the complete answer regarding the over-all suitability of the brush for the application. However, meticulous attention to test procedures reduces the usual degree of dependence upon inexact observational measurements, reduces the hazards of possible wrong decisions in the selection of brushes, and greatly improves the usefulness of observational measurements because of the sound background of other factors on which they are based.

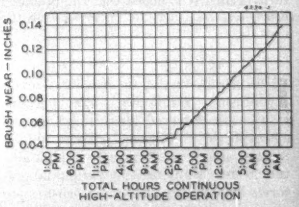


Figure 5. Brush wear versus time

Quick changes to a new greatly increased rate of wear often are encountered at high altitude

Table I

Atmospheric Conditions	Class I Free Air External	Class II Fuselage—Air Within the Airplane	Class III Supercharged Compartment	Class IV Engine Nacelle
Altitude in feet	40,000	40,000	15,000	40,000
Dew point in degrees centigrade	−50 to −80	−50 to −80	−50 to −80	−50 to −80
Ambient-temperature air in degrees centigrade				
(a). Surrounding the machine	−40	0	0	+38
(b). Rammed air 6 inches from machine intake ports				−30*
Rammed-air pressure (Sum of velocity and pressure head measured with Pitot tube at least 6 in. away from machine intake ports. See Figure 2)				6-in. water*

* Conditions do not apply to self-ventilated machines.

Appendix. Brush-Qualification Test Procedure

The following specific rules have been found desirable in conducting brush tests:

1. INITIAL INSPECTION

Carefully check the machine to make sure it has not been damaged mechanically in any important particular. Make sure that balance is satisfactory as evidenced by ac-

ceptable vibration, that end-play adjustment is correct, that brushes are free in brush holders with springs in proper place and with brush pressure correctly adjusted, and that commutator or ring run-outs on bearings meet standard limits for the equipment.

2. Preparation for Test

On freshly ground, turned, or polished commutators or rings, operate units approximately five hours at light loads to obtain a satisfactory brush seat and to establish approximately normal brush film on commutators, rings, or other current collecting surfaces.

Many machines will not give satisfactory performance characteristics until the brushes are seated properly. It generally is desired to have brushes seated 100 per cent before beginning tests, but where this is not practical due to limited time, brush seats equal to or better than those shown in Figure 1 have been found satisfactory. All brushes must be seated 75 per cent of face area and 100 per cent of brush thickness for 50 per cent of the brush width. Where there are two or more brushes per stud, all brushes on one stud are to be considered one brush so far as brush seat is concerned.

3. Measurements and Methods

The measurements and observations listed in sections *a*, *b*, *c*, and *d* generally are taken at the beginning of the brush test, at the conclusion of the normal-altitude runs, and again at the conclusion of the high-altitude runs. During continuous-duty test runs, the test readings listed in sections *e*, *f*, *g*, and *h* generally are taken every ten minutes until the machine and associated test apparatus reach reasonably steady operating conditions. Then the intervals may be lengthened up to one hour or more. To insure detection of all significant changes, recording instruments should be used wherever possible.

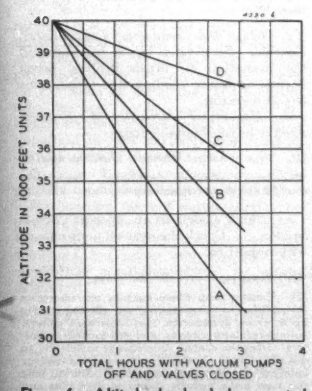
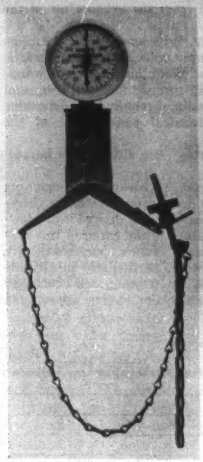


Figure 6. Altitude-chamber leakage control

A and *B* = worst and best conditions over one month interval = adequate tightness to obtain −50-degree-centigrade dew point

C = best obtainable after leaks around screws through the walls were sealed

D = a second chamber with an improved door seal



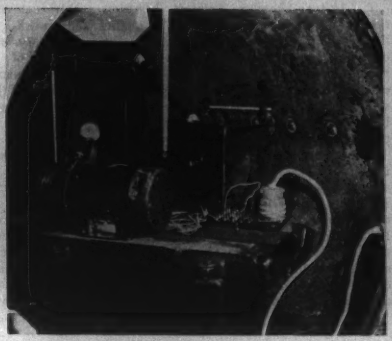


Figure 7 (left). Brush-wear indicating device

Figure 8 (above). Test machine with brush-wear indicator in altitude chamber

a. Commutators. Measure diameter, total gauge, and bar-to-bar run-out in the brush track. Where experience indicates there is any possibility of bar movement, commutator run-outs also should be checked outside the brush track. Note any irregularity across the face of the individual bars, such as "crowning," indicating faulty machining.

Inspect undercuts for any evidence of feather-edge mica, excessive burrs, foreign material.

b. Slip Rings. Check diameters, gauge run-outs, and note any evidences of faulty machining, such as wavy surface.

c. Brush Lengths. Due to the wide variety of shapes, no standard method of designating brush length can be used. Generally measure lengths from the same locations shown on the brush drawing for the particular machine. Measuring to the edges of brushes is often necessary and is satisfactory if micrometers are used very carefully to prevent crushing of the brush edges.

Brushes should be numbered by scriber or other means on a suitable surface for test identification and for location identification for further measurements. Brush wear is often only a few thousandths of an inch during the practical test time used. Therefore, great care in taking measurements is necessary if large percentage errors are to be avoided.

Wherever practical, the use of a continuous-indicating brush-wear device is recommended. The device should have extremely small inertia and have no measurable affect upon brush pressure. A dial-type indicator which has these characteristics, is free from backlash, and is easy to attach to the brush is pictured in Figure 7. A typical installation of the wear gauge in use on a test unit in an altitude chamber is shown in Figure 8.

d. Brush-Spring Pressures. Measure with brush in the location corresponding to its riding position on the commutator or ring. With many mechanisms the pressure may be determined easily by measuring the pull necessary to lift the spring off the top of the brush. On other types where the spring is maintained in position on the brush and the pressure is measured at the brush face, the brush mechanism should be vibrated during these measurements to eliminate the affects of friction in holders. Note any brushes which have sluggish or sticky action in the brushholders.

e. Machine Temperatures. These are taken on all parts where temperature affects the life and reliability of that part, or of the brushes. In general, the minimum points of measurement are as follows:

(1). Two motor brushes (one of each polarity). On small brushes with face area less than one-tenth square inch, the use of five-mil wire thermocouples is recommended. Whatever the brush size may be, it is important that the thermocouples have sufficient flexibility and that they are carefully installed to prevent any interference with brush movement. To permit brush wear during tests, thermocouples usually are installed one-fourth to three-eighths inch away from the brush face. Figure 4 indicates the need for measuring brush temperatures whenever possible.

The brush face temperature is the basic measurement needed. Therefore, thermocouples should be installed as close to the brush face as rate-of-wear conditions during the practical test time will permit. The temperature gradient between brush face and thermocouple location will vary greatly among different brush materials and with different ventilations. The gradient on nonmetallic brushes will be relatively high.

To avoid erroneous thermocouple readings due to stray currents, it is desirable to keep thermocouples electrically insulated from the brushes and the machine. Wire insulating varnishes have been used to insulate the thermocouple tips in a manner that causes very little temperature gradient between the thermocouple and the brush.

(2). Each slip-ring brush.

(3). Each bearing housing as close to the bearing as possible.

(4). Motor case.

(5). Field windings or other stationary windings.

f. Altitude-Chamber Ambient Temperatures. Ventilation conditions in chambers are often far from ideal, because the chambers are relatively small; temperature gradients, air turbulences and flows may exist in connection with the refrigerating systems; and large gradients may exist between the chamber wall and case temperatures of the machine under test.

Check temperature on the chamber walls, in air six inches from the test machine intake air ports, and at as many other points as necessary to determine average air ambient temperature six inches from the test unit. In rammed-air-cooled machines the temperature should be taken in the center of the air duct six inches from the surface of attachment of air duct to the machine. Keep ambient-temperature thermometers appreciably removed from the exhaust air of the test unit.

g. Machine Performance. Take measurement of: input volts, amperes, and watts; speed; output volts, amperes, and watts; output or input torque; field amperes; and any other readings required to determine completely electrical performance of the machine.

h. Altitude. Use altimeter or barometer.

i. Dew Point. Measure at beginning of test and at least every five hours thereafter. The measurement desired is the dew-point temperature of air entering test machine. Accurate values sometimes are difficult to obtain, particularly in altitude chambers. When testing self-ventilated machines in chambers having appreciable leakage, it is important to measure dew point of air near intake of test unit. A method for this is shown in Figure 2.

With negligible leakage, it would be adequate to measure dew point in only the dry-air supply lines to the chamber. Typical leakage-control tests are illustrated in Figure 6. Experience indicates that leakage control to assure low dew point is the most critical problem in high-altitude chamber operation. One cubic foot of leakage air may carry as much moisture into chamber as several thousand cubic feet of air from an alumina dryer.

CARBON BRUSH TEST REPORT

Tested at	Works in Bldg.		Machine Model	
Serial Number of Test				
Machine Serial Number				
*Ring or *Commutator Metal				
Where Was Metal Obtained?				
Brush Grade and Treatment				
Where Were Brushes Obtained?				
Atmosphere (air, nitrogen, etc.)				
Refrigerant (dry ice, Freon, etc.)				
Dew Point (°F or °C)				
Altitude—Feet				
Machine Speed in RPM				
Load Amperes				
Brush Density—Amps/Sq In.				
Field Current—Amps				
Ambient Temp (°F or °C)				
"Air In" Temp (°F or °C)				
Brush Temp (°F or °C) Max.-Min.				
Brush Temp (°F or °C) Average				
Ring or Comm. Temp (°F or °C)				
Spring Force—Oz Ave. Initial				
Spring Force—Oz Ave. Final				
Friction Watts Max.-Min.				
Friction Watts Average				
Brush Contact Drop Max.-Min.				
Brush Contact Drop Average				
Hours Tested—Total				
Hours Tested at Altitude				
Actual Brush Wear—Inches				
Indicated Brush Life per ¼"—Hours				
Ring or Comm. Wear (Diam) Inches				
Date of Test				

REMARKS: Commutation, Film Condition, Vibration, Ventilation, Reason for Stopping Test, etc.

*Indicate which Date Signed

Figure 9. Brush-test report

4. General Factors Indicating Brush Suitability, Troubles, and Probable Causes

Observations of the following will assist in judging brushes and diagnosing trouble.

a. Surface Condition of Commutator or Slip Rings

(1). Bar-to-bar burning, uniform or nonuniform.

(2). Wearing out-of-round.

(3). Ring grooving or threading, severity and stability.

(4). Skip burning. Note any evidence which indicates the cause (bad mechanical run-outs, faulty brush mechanisms, bad rotor balance, defective bearings, brush overfilming).

(5). Uneven film.

(6). Indications of polarity spots when collecting alternating current on slip rings.

b. Uniformity of Brush Wear. The following possibilities should be investigated when wear of individual brushes deviates more than plus or minus 20 per cent from average:

(1). Polarity effects of brush material.

(2). Uneven spacing of holders.

(3). Uneven brush-spring pressures.

(4). Brushes stuck in holders or binding of pivoted holders.

(5). Brushes incorrectly positioned (wrong electrical shift).

c. Brush and Commutator Temperatures. Consider effects upon life of bearings and the insulation on brush holders, brush shunts, armature winding, and connections to commutator.

d. Mechanical Strength of Brushes. Are the brushes suitable for:

(1). Type of holder? Consider brush sidewear.

(2). Service vibration conditions? Particularly consider the shunt connections.

e. Effects of Brushes on Machine Characteristics. Check the over-all performance with respect to:

(1). Power input over the load range.

(2). Contact drop where machine characteristics (in addition to commutation) are affected greatly by it, as on dynamotors, speed-regulated motors, voltage-regulator circuits, and self-excited generators. Does the contact drop change sufficiently to disturb voltage regulation or to prevent voltage build-up of self-excited generators? During long test runs make periodic checks to determine any marked changes in contact drop.

(3). Commutating ability for expected manufacturing variations of a particular class of machines.

(4). Consistency of performance:
From zero to high current densities.
From low to high humidity.
From lowest to highest operating temperature.

(5). Brush riding characteristics, as indicated by ripple voltage, radio-interference filter requirements, and amount of brush chatter over operating range.

5. General Precautions for High-Altitude Tests

a. Altitude. Maintain within plus or minus 1,000 feet.

b. Ambient Temperature. Maintain within plus or minus five degrees centigrade.

c. Contamination. Admit fresh air into the altitude chamber continuously to avoid accumulation of contaminating vapors.

The vapors from bearing greases, incompletely cured paints, and insulating varnishes of new machines have greatly improved the high-altitude brush wear in specific chamber tests, until the most volatile constituents evaporated and insufficient contamination remained to lubricate the brushes. On totally enclosed or only slightly ventilated machines, this self-contamination may be pronounced, and there is often a great difference in brush performance on new and old machines.

When practical, recirculation should be avoided and only fresh air admitted to the test machine. This can be done readily with pressure-ventilated machines, but is not feasible for most self-ventilated units because of interference with ventilation and radiation. Experience with recirculating ventilated chambers indicates that contamination usually becomes negligible if the chamber air is changed five to ten times per hour. The recommended frequency of changes depends on the relative size of chamber and test units.

A chamber with recirculation should not have thermal insulation, braid-covered leads, varnish-cloth tape, wooden platforms, or other absorbent materials inside. It should be cleaned thoroughly before every test. Steam cleaning followed by a bake to dry out all moisture has been found satisfactory. The chamber should be flushed with dry air before refrigerating. The walls and cooling coils, if any, should not accumulate objectionable frost during an altitude test.

d. Need for Long Tests. On high-altitude trials of less than one hour, indicated brush life may be many times that obtained on a continuous-run-to-destruction. Some altitude-protected brushes may operate well for ten hours or more, and then suddenly dust, overheat, become unstable, cause excessive friction, or high-contact drop. It is important to take relatively long trials as may be noted in Figure 4.

e. Initial Equilibrium Conditions. High-altitude conditions usually are established before starting the test machines, thereby providing a more severe test for the brushes. Climb and dive cycles sometimes must be simulated, but unless otherwise specified, equilibrium conditions should be established first.

6. Duration, Repetition, and Sequence of Tests

Tests should be taken at rated speed, voltage, load (or load cycle), or at defined specification conditions.

a. Duration of Low-Altitude Tests. A qualification life test should be a minimum of 300 hours, or 25 per cent of guaranteed life, whichever is shorter.

b. Duration of High-Altitude Tests. A qualification life test should be a minimum of 30 hours, or 25 per cent of guaranteed life, whichever is shorter. If necessary, the test may be divided into minimum runs of 15 hours or more with intervening low-altitude trials.

c. Repetition of Tests. Because of variations in machine and test conditions, the results with three or more different units should be averaged to obtain representative brush life for a specific machine design. When only a single machine is used for tests, the results from two or more life tests should be averaged to obtain representative brush life for the particular machine.

d. Sequence of Tests. Low-altitude tests usually are taken prior to high-altitude tests because:

(1). The film formed at low altitude may influence the high-altitude performance. Most units operate initially at low altitudes in actual service.

(2). Some brushes lose their high-altitude protection during extended runs. This characteristic might not be revealed by a short-altitude test only.

(3). Mechanical deterioration of machines adversely effects brush performance. Chamber tests should simulate such unfavorable conditions as are likely to exist in flight.

(4). The more volatile components of lubricants, insulating varnish, and motor paint tend to be driven off during extended low-altitude runs. This reduces contamination of the altitude chamber.

7. Methods of Reporting Test Results

To assist in reporting all significant facts, a standard test data form similar to Figure 9 is recommended.

Solderless Terminals

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IN the last few years solderless terminals have found an increasingly wide application. The fields of application include aircraft, shipboard, communication, and general industrial work. One of the most important reasons for their increasing use is the substantially decreased labor required in their application, as compared to soldered terminals. The use of solderless terminals also gives assurance of a greater degree of uniformity with respect to both mechanical and electrical properties for the terminal conditions of the electric circuit. Furthermore, these terminals are more readily adaptable for such improvements as insulation supports for the wire insulation to which the solderless terminal is crimped and the use of a preinsulated terminal. In general, the use of solderless terminals in both manufacture and application permits machine production and uniformity as compared to handwork necessary for soldered terminals.

Description

A type of solderless terminal is shown in Figures 6 and 10. These terminals consist of a tongue or lug for terminal-block connection, and an internally serrated barrel with sleeve for crimping to the wire. In general, the stranded wire with insulation stripped off the end is inserted for the full length of the barrel, and then two adjacent lateral crimps are applied. This crimping may be accomplished by either a hand tool or a machine press. An enlarged picture of this terminal through one of the crimp sections for a 19-strand wire is shown in Figure 1. The section has been etched with a solution of ammonium hydroxide and concentrated hydrogen peroxide to indicate clearly the individual strands of wire following crimping. Sufficient pressure is exerted in the crimping operation to give a flow of metal, so that maximum contact area between the strands and between strands and terminal barrel is obtained. This gives maximum electrical conductivity for a given volume of metal. Furthermore, this would give maximum tensile strength for the terminal, and also would give a minimum number of longitudinal channels for entrance of corrosive liquids or condensates. In general, the crimp is designed to give a tensile strength of the wire to the crimped joint approximately equal to that of the stranded wire itself. Comparative tensile-strength test results are shown in Figure 2. In these tests failure was obtained by breaking of the stranded wire itself rather than by the stranded wire pulling out of the crimped joint. The differences between the tensile strengths of the stranded wire itself and of the stranded wire when crimped to a terminal is due to different methods of terminating the wire in the two cases, with better equalization of individual strand stress being possible in the first case.

Soldered Terminals

Since soldered terminals have been used for a long time, it is perhaps natural that any other method of adapting a terminal to a wire would be analyzed in comparison with the performance of a soldered terminal. Certain of the inherent difficulties in obtaining a satisfactory soldered joint are not generally appreciated. For electric conductors

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tin–lead solder is generally used with either copper terminals or tinned-copper terminals and wire. A properly soldered joint is dependent, however, on the simultaneous achievement of cleanliness of metal surfaces and sufficient heating of the parts to be soldered. A successfully soldered joint involves the actual alloying of the soldered parts with the solder itself. Insufficient heat will cause the solder only to wet the metal, but not to alloy with it. Since there is no difference in the appearance of the two types of soldered joints, it is extremely difficult to determine whether two metals are soldered properly. The presence of large beads of solder on a joint does not mean necessarily that the metals have been soldered properly. In fact, unnecessary solder prolongs the cooling time and enhances the possibility of movement of the parts to be joined, causing the solder to crystallize, thereby weakening the joint.

In general, the electrical conductivity stability of a properly soldered joint is practically constant under long-time corrosion conditions. However, improperly soldered joints have shown relatively large increases in resistance under corrosion conditions. Such increases may be of the order of a few hundred per cent or more, depending upon the degree of departure from ideal soldering conditions.

Test Procedures and Measurements

One of the most important electrical characteristics of a terminal or electric connection is the stability of the electrical conductivity. This may be determined by an electrical-resistance measurement. The initial resistance is of importance, since it is a measure of the electrical efficiency of the contact as a conducting medium. The change in resistance under corrosion conditions is of importance, since it will determine the electrical stability of the contact under operating conditions. This stability under operating conditions is particularly important, since any great increase in resistance generally gives increased operating temperatures and a consequent increase in the corrosion rate.

Since corrosion plays a large part in determining the relative electrical stability of a solderless terminal, the design and metallic composition of a terminal must of necessity preclude any extensive corrosion. The terminal must be able to withstand operating conditions in which it may be exposed to high humidities, natural waters, chemical salts and brines,

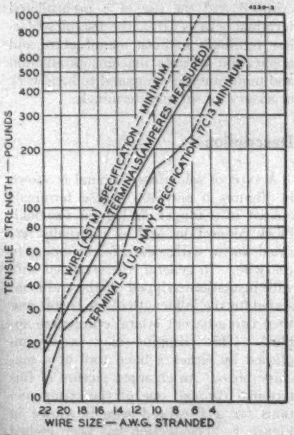


Figure 2. Tensile strengths—terminals and wire

and high temperatures. The terminal must be crimped in such a manner that no corrosion occurs because of cracking or fatigue in the metal. The metal used in the construction of the terminal must be such as to obviate any electrochemical corrosion due to galvanic action between the terminal and the wire.

Electrical measurements of resistance of solderless terminals of the type described in this paper have been made under the following types of corrosion conditions:

1. Continuous four per cent sodium-chloride spray.

2. Continuous ten per cent sodium-chloride spray.

3. Continuous four per cent sodium-chloride with 0.1 per cent sodium-hydroxide spray.

4. Alternating four per cent sodium-chloride spray and circulating-air oven at 100, 133, 166, and 200 degrees centigrade.

5. Alternating four per cent sodium-chloride and 0.1 per cent sodium-hydroxide spray with 100 degrees centigrade circulating-air oven.

6. Relative humidity of 85 per cent alternating with 100 degrees centigrade circulating-air oven.

7. Alternation of 100 degrees centigrade circulating-air oven, four per cent sodium-chloride spray, and vibration test at $^1/_{32}$-inch amplitude at a frequency of 2,000 cycles per second—vibration test made to give flexing of stranded wire relative to terminal.

8. Sulphur dioxide vapor.

9. Alternating and direct currents corresponding to approximately three times normal rated currents for periods of three-fourths hour, alternating with different salt-spray tests.

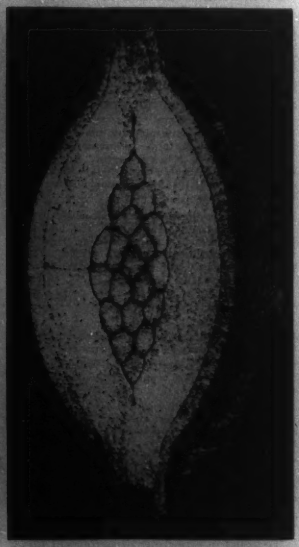


Figure 1. Enlarged picture of crimped solderless terminal

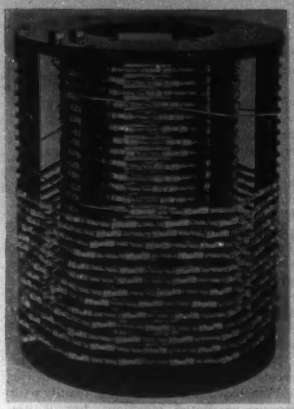


Figure 3. Assembly of 1,000 solderless terminals for electrical measurements during corrosion tests

The foregoing corrosion tests have been made on different terminals for varying periods of time. In certain cases they have been continued for a period of 150 days. It is believed that such corrosion conditions are very much more severe than those normally encountered in any application, but they may be considered as accelerated tests. In addition, they indicate the particular characteristics of a given type of corrosion or the relative efficiency of different types of terminals, with respect to either materials or construction.

Electrical measurements of resistance have been made using both alternating and direct current, with the currents varying from ten microamperes up to those substantially greater than the normal rating of the wire. Resistance

Figure 4. Detail of connector

measurements of this type generally fall in the range from one milliohm to one microhm. The measuring circuits that have been used include the Kelvin–Thomson bridge, potentiometer, and comparison methods. In general, any of these methods may be used with either alternating or direct current. For relatively low resistances with low currents the use of alternating current is to be preferred, in view of the facility with which sensitivity may be increased by amplification. The use of alternating current also eliminates difficulties due to thermal and contact-voltage effects. For the measurement of very low voltages, the use of a tuned circuit such as a wave analyzer is desirable. In general, any of the methods will give a sufficient precision and accuracy with appropriate equipment and calibration.

Test Results

Measurements of the electrical resistance of solderless terminals have been made using different types of corrosion tests with different contact metals over very wide ranges of current, under different temperature conditions for both the measurements and the corrosion tests.

Resistance of Solderless Terminals Over a Wide Range of Current

Measurements of electrical resistance of solderless terminals over a range of current from ten microamperes to ten amperes in decade steps are given in Table I. These measurements were made on an assembly of 500 connectors as shown in Figure 3. The connector is shown in Figure 4; each connector includes two regular crimped solderless terminals with a short strip or link between the individual terminals. Thus, the assembly in Figure 3 consists of a series connection of 1,000 solderless terminals or crimped joints. The connectors are number 16–14 with 19-strand number-14 American Wire Gauge insulated tinned-copper wire. The connectors as shown in Figures 4 and 5 are joined with a short length of insulated wire to give a seven-eighths-inch length of wire between adjacent faces of the connectors. The resistances in ohms in Table I are indicated by R_1 in Figure 5, and include one crimp plus a $^7/_{16}$-inch length of stranded number-14 wire plus one half of the link between connectors. The type of corrosion used in this test consisted of a combination of four per cent salt spray for a period of 24 hours followed by an equal period in a circulating-air oven at 100 degrees centigrade.

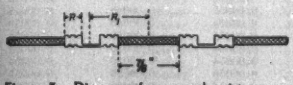


Figure 5. Diagram of measured resistances—connector

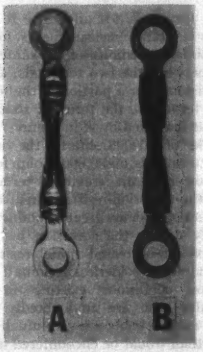


Figure 6. Solderless terminals for resistance measurements during corrosion tests

The results in Table I were measured at room temperature (20 degrees centigrade), and at an elevated temperature approximating 100 degrees centigrade. In the current range from one milliampere to ten amperes the resistance measurements were made using alternating current at a frequency of 60 cycles per second, and below this current range they were at a frequency of 100 cycles per second. The test results show that the resistance of the solderless terminals is independent of the current over the range from ten microamperes to ten amperes. This applies to resistance measurements at both room temperature and at 100 degrees centigrade. In this case the corrosion test was continued for a period of 108 days, which would normally be considered an extreme in terms of standard accelerated corrosion tests.

Comparison of Tinned-Copper Solderless Terminals and Wire With Corrosion-Resistant-Treated Solderless Terminals

The resistance measurements shown in Tables II and III give a comparison of resistance stability during corrosion of a tinned-copper terminal crimped to tinned-copper wire (Table II) with a corrosion-resistant-treated copper terminal and tinned-copper stranded wire (Table III). These resistance measurements were made using two solderless terminals mounted back to back, as shown in Figure 6. The terminals are of a type with an insulation support. The terminals are number 22-16 with seven-strand number-18 insulated wire. The resistances in ohms given in Tables II and III are indicated by R_1 in Figure 7 and include two crimped or solderless terminals plus five-eighths inch of wire plus a portion of each lug of each terminal. The corrosion cycle consisted of passing 15 amperes alternating current,

Figure 7. Diagram of measured resistances—terminal

Figure 8 (left). Extent of corrosion—28-day salt-spray test

Figure 9 (right). Series connection of solderless terminals

Table I. Resistance of Solderless Connectors at Currents Indicated

Duration of Corrosion Test—Days	Microamperes		Milliamperes			Amperes	
	10	100	1	10	100	1	10
Resistance Measurements at Room Temperature (20 Degrees Centigrade)—Ohm							
0	0.00019	0.00019	0.00019	0.00019	0.00018	0.00018	0.00018
8	0.00019	0.00019	0.00019	0.00019	0.00019	0.00019	0.00019
18	0.00019	0.00020	0.00020	0.00020	0.00020	0.00020	0.00020
28	0.00019	0.00020	0.00020	0.00020	0.00020	0.00020	0.00021
33	0.00019	0.00020	0.00020	0.00020	0.00020	0.00021	0.00021
42	0.00020	0.00020	0.00020	0.00020	0.00020	0.00020	0.00020
49	0.00020	0.00021	0.00021	0.00021	0.00021	0.00021	0.00021
55	0.00021	0.00021	0.00021	0.00022	0.00021	0.00021	0.00021
62	0.00021	0.00022	0.00022	0.00022	0.00021	0.00021	0.00021
69	0.00021	0.00022	0.00023	0.00023	0.00022	0.00022	0.00021
76	0.00022	0.00024	0.00024	0.00024	0.00022	0.00022	0.00022
83	0.00025	0.00025	0.00025	0.00025	0.00022	0.00022	0.00022
90	0.00025	0.00025	0.00025	0.00025	0.00023	0.00023	0.00023
98	0.00024	0.00024	0.00024	0.00024	0.00023	0.00023	0.00023
108	0.00024	0.00023	0.00023	0.00023	0.00024	0.00024	0.00024
Resistance Measurements at Approximately 100 Degrees Centigrade—Ohm							
49	0.00038	0.00028	0.00028	0.00028	0.00028	0.00028	0.00027
55	0.00028	0.00028	0.00028	0.00028	0.00028	0.00028	0.00027
62	0.00028	0.00028	0.00028	0.00028	0.00028	0.00027	0.00026
69	0.00028	0.00028	0.00028	0.00028	0.00028	0.00028	0.00028
76	0.00028	0.00029	0.00028	0.00028	0.00028	0.00028	0.00028
83	0.00028	0.00028	0.00029	0.00028	0.00028	0.00028	0.00028
90	0.00030	0.00030	0.00030	0.00030	0.00029	0.00029	0.00029
98	0.00030	0.00030	0.00030	0.00030	0.00029	0.00029	0.00029
108	0.00030	0.00030	0.00020	0.00020	0.00032	0.00032	0.00031

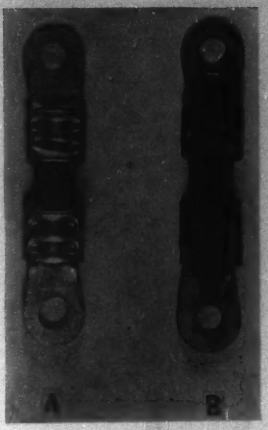


Figure 10. Solderless terminals

A—Before corrosion test

B—After 28-day corrosion test

60 cycles per second, through the terminals for 45 minutes, followed by 7¼ hours in ten per cent salt spray, after which the salt spray was shut off, although the samples were allowed to remain in the salt-spray chamber for the remainder of the 24 hours. Certain standard specification tests have used a similar corrosion cycle. It has been found for the high-current portion of the corrosion cycle that, if the tongue of the corroded terminals is adequately cleaned for contact purposes, no perceptible heating of the terminals will ensue. However, if contact with corroded terminals is made without cleaning of the contact points where current enters the terminals under test, excessive heating of the terminals will occur. These temperatures may be in the range of 100 to 200 degrees centigrade or higher, depending upon the extent of the corrosion where contact is made. However, such heating is at the contact points where current is brought into the terminal assembly and is not due to the resistance of the solderless terminal itself. For these particular tests groups of pairs of terminals, shown in Figure 6, were connected in series by bolted connections, as shown in Figures 8 and 9. Figures 8 and 9 show the extreme corrosion products formed after a period of 28 days or 28 corrosion cycles. A considerable portion of the corrosion products that are shown results from the plated iron machine screw and nut that were used to bolt the terminals together. The resistance measurements given in Tables II and III were made across each pair of terminals, as shown in Figure 6. The results indicate a practically constant electrical resistance for the corrosion-resistant terminals throughout the corrosion test, as compared to an approximate 75 per cent increase for the regular tinned-copper terminals. If allowance is made in the resistance measurements for the approximate resistance of the connecting wires between the two terminals, and of the resistance for a portion of the tongue of the terminals, the terminal resistance itself, as indicated by *R* in Figure 7, is of the order of 0.00008 ohm for the tinned-copper terminals, and 0.00005 ohm for the corrosion-resistant-treated terminals. Thus, the corrosion-resistant-treated terminal not only shows greater conductivity stability during the corrosion test, but also gives a decreased initial resistance per crimped or solderless terminal. The corrosion conditions existing in this particular test are undoubtedly very severe, and probably are very much more severe than would be encountered in any practical application.

Conductivity Stability of Relatively Large Solderless Terminals Under Corrosion

The foregoing measurements of the electrical resistance of solderless terminals during corrosion have been made on stranded wire sizes 14 and 18 with corresponding terminals. Tests also have been made on stranded wire sizes 4 and 6 with corresponding terminals. These tests have been made on two terminals mounted back to back as shown in Figure 10. Figure 10, part *A*, shows the terminal before the start of the corrosion test, and Figure 10, part *B*, shows the terminal after 28 days' salt-spray corrosion.

Figure 11 shows the resistance of the terminals and wire as a function of corrosion time or cycles during the test and includes:

Graphs 1 and 3, tinned-copper terminals with tinned-copper wire.

Graphs 2 and 4, corrosion-resistant-treated copper terminals with tinned-copper wire.

Graphs 1 and 2, number 6 terminals with stranded (181 strands) wire.

Graphs 3 and 4, number 4 terminals with stranded (132 strands) wire.

The corrosion cycle consisted of eight hours of four per cent salt spray and 16 hours of circulating-air oven at 100 degrees centigrade. The resistances are measured in a manner corresponding to the diagram shown in Figure 7, and in-

Table II. Resistance of Solderless Terminals—Tinned-Copper Terminal—Tinned-Copper Stranded Wire

Duration of Corrosion Test—Days	Ohm				
	No. 1	No. 2	No. 3	No. 4	Average
0	0.00046	0.00046	0.00052	0.00046	0.00048
2	0.00046	0.00046	0.00052	0.00046	0.00048
3	0.00048	0.00047	0.00054	0.00050	0.00050
8	0.00050	0.00051	0.00054	0.00050	0.00051
12	0.00057	0.00052	0.00054	0.00055	0.00054
14	0.00055	0.00052	0.00054	0.00056	0.00054
16	0.00056	0.00052	0.00056	0.00056	0.00055
23	0.00072	0.00051	0.00054	0.00061	0.00060
28	0.00096	0.00062	0.00096	0.00067	0.00080

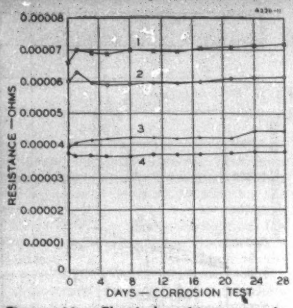


Figure 11. Electrical resistance–corrosion time of corrosion-resistant tinned terminals

Table IV. Resistance of Solderless Terminals—Strand to Terminal

Strand Number	Duration of Corrosion Test—Days						
	0	13	27	34	44	50	57
1	0.0036	0.0037	0.0038	0.0036	0.0039	0.0035	0.0035 ohm
2	0.0040	0.0040	0.0041	0.0045	0.0041	0.0039	0.0038 ohm
3	0.0038	0.0039	0.0041	0.0041	0.0041	0.0039	0.0039 ohm
4	0.0038	0.0038	0.0039	0.0040	0.0040	0.0037	0.0035 ohm
5	0.0038	0.0038	0.0038	0.0037	0.0039	0.0037	0.0036 ohm
6	0.0038	0.0039	0.0038	0.0037	0.0041	0.0039	0.0037 ohm
7	0.0037	0.0038	0.0038	0.0037	0.0039	0.0036	0.0035 ohm
8	0.0041	0.0043	0.0044	0.0044	0.0045	0.0042	0.0041 ohm
9	0.0041	0.0044	0.0045	0.0044	0.0046	0.0044	0.0042 ohm
10	0.0038	0.0041	0.0043	0.0043	0.0042	0.0041	0.0039 ohm
11	0.0038	0.0042	0.0043	0.0045	0.0043	0.0041	0.0039 ohm
12	0.0041	0.0043	0.0044	0.0044	0.0045	0.0043	0.0041 ohm
13	0.0039	0.0041	0.0042	0.0041	0.0043	0.0040	0.0039 ohm
14	0.0039	0.0043	0.0043	0.0042	0.0044	0.0041	0.0039 ohm
15	0.0040	0.0046	0.0045	0.0045	0.0046	0.0044	0.0042 ohm
16	0.0039	0.0043	0.0043	0.0043	0.0044	0.0041	0.0039 ohm
17	0.0039	0.0043	0.0043	0.0044	0.0044	0.0042	0.0040 ohm
18	0.0038	0.0042	0.0043	0.0043	0.0044	0.0041	0.0040 ohm
19	0.0040	0.0043	0.0045	0.0045	0.0045	0.0043	0.0041 ohm

clude two terminals plus one-half-inch to five-eighths-inch wire, plus portions of the tongue of each terminal. The results show relatively good conductivity stability for both sizes of wire and for both types of terminals, the best stability being obtained with the corrosion-resistant-treated terminals. Furthermore, the resistance of the corrosion-resistant terminal is significantly less than for the tinned-copper terminal. Making appropriate allowance for the resistance of the wire and tongue in the measurements given in Figure 11 gives a value for the initial barrel resistance (R in Figure 7) of the number-4 and number-6 tinned-copper terminals of approximately 0.000014 and 0.000009 ohm, respectively, and of the number-4 and number-6 corrosion-resistant terminals 0.000011 and 0.000007 ohm, respectively.

Resistance Measurements on Individual Strands of a Stranded Wire With a Solderless Terminal

Previous resistance tests on solderless terminals have been made from one terminal to another terminal. In this case, however, resistance measurements have been made from each strand of a stranded wire to the solderless terminal crimped to the group of stranded wires. The purpose of these tests is to determine the uniformity of the resistances from the different strands to the terminal. Measurements were made on an assembly, as shown in Figure 12, with the results being given in Table IV. A wire with 19 strands was used in which strands 1–12 inclusive were in the outer layer, 13–18 inclusive were in the intermediate group, and 19 was the central strand. The results in Table IV give the resistance measurements made on each strand at different lengths of time during a 57-day corrosion test. The corrosion test consisted of a cycle of 24 hours in four per cent salt spray followed by 24 hours in a 100 degrees centigrade circulating-air oven. In measurements of this type it is not possible to obtain a high degree of uniformity among the individual measurements shown in Table IV in view of the high resistance of the individual strand and the variable length of the individual strands. However, the results do indicate both a reasonable uniformity of individual-strand resistance measurements and a satisfactory conductivity stability for the individual strands.

Effect of Different Contact Metals With Copper

Previous test results have been obtained using regular tinned-copper terminals crimped to tinned-copper wire. The results in Figure 13 gave a comparison of the electrical resistance as a function of corrosion time, using graph 1, copper terminal with tinned-copper stranded wire; graph 2, tinned-copper terminal and tinned-copper stranded wire; graph 3, corrosion-resistant-treated terminal and tinned-copper wire. These tests were made using number-22-16 terminals with seven-strand number-18 wire. The measurements were made on two terminals mounted back to back, as shown in Figure 6, and include the resistance R_1 as indicated in Figure 7. The corrosion-test cycle consisted of four per cent salt spray for eight hours, followed by 16 hours in a circulating-air oven at 100 degrees centigrade. The test was continued for a period of 28 days. The curves in Figure 13 show that the greatest increase in resistance was obtained with the copper terminal on tinned-copper wire (graph 1). This increase in resistance may be considered to be due to the oxidation of the copper and to the galvanic action resulting from the two different contact metals. The greater conductivity stability of the tinned-copper terminal to the tinned-copper wire (graph 2) as compared to graph 1, copper terminal to tinned-copper wire, is due both to the absence of any electromotive force between the different contact metals and to the greater chemical stability of the tin. Graph 3 shows the improved conductivity stability of the corrosion-resistant-treated copper terminal and tinned-copper wire. This is due to the fact that both corrosion and contact electromotive forces due to different metals have been effectively eliminated in this terminal. It is also of interest in studying Figure 13 to note that the terminals with the greater conductivity stability with corrosion time have the lower initial resistance. Since these differences in the initial resistances are due to differences in the barrel resistances, R of Figure 7, and since the initial resistances include some wire resistance, the differences between the barrel resistances are proportionally much greater than those indicated.

Table III. Resistance of Solderless Terminals—Corrosion-Resistant Treated Copper Terminal—Tinned-Copper Stranded Wire

Duration of Corrosion Test—Days	Ohm						
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	Average
0	0.00043	0.00042	0.00043	0.00042	0.00043	0.00043	0.00043
1	0.00043	0.00043	0.00043	0.00042	0.00043	0.00043	0.00043
4	0.00043	0.00043	0.00043	0.00042	0.00042	0.00043	0.00043
6	0.00040	0.00040	0.00040	0.00038	0.00040	0.00040	0.00040
8	0.00041	0.00041	0.00043	0.00038	0.00041	0.00041	0.00041
11	0.00041	0.00041	0.00042	0.00040	0.00040	0.00042	0.00041
13	0.00042	0.00040	0.00042	0.00038	0.00040	0.00041	0.00040
17	0.00041	0.00041	0.00040	0.00039	0.00040	0.00041	0.00040
19	0.00041	0.00040	0.00041	0.00039	0.00041	0.00040	0.00040
21	0.00041	0.00041	0.00042	0.00039	0.00040	0.00042	0.00041
28	0.00041	0.00041	0.00041	0.00036	0.00038	0.00041	0.00040

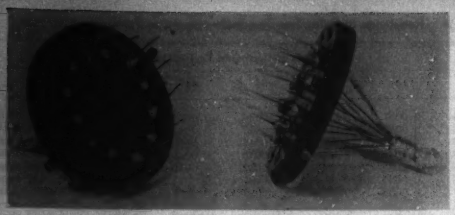
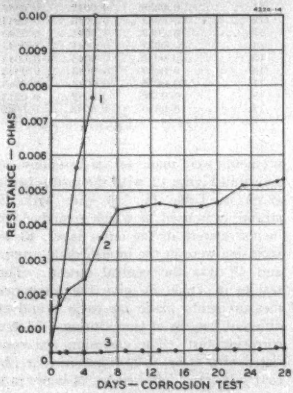


Figure 12. Assembly — electrical measurements strand to solderless terminal

Figure 14 (below). Electrical resistance—corrosion time of different contact metals—aluminum wire



The Effect of Different Contact Metals With Aluminum

The curves in Figure 14 give the relative conductivity stability of different types of terminal metals with stranded aluminum wire. Graph 1 shows the results with a tinned-copper terminal with aluminum wire; graph 2 shows an aluminum terminal with aluminum wire; graph 3 shows a specially treated terminal and aluminum wire. These tests were made using number-22-16 terminals with seven-strand number-18 wire. The terminals were mounted back to back as shown in Figure 6. The resistance in ohms in Figure 14 is shown by R_1 in Figure 7 and includes portions of each lug plus two crimps, plus five-eighths inch of wire. The corrosion cycle consisted of eight hours of four per cent salt spray and 16 hours of circulating-air oven at 100 degrees centigrade. The greatest increase in resistance is obtained with the tinned-copper terminal to the aluminum wire, since in this case the increase in resistance is due both to galvanic action because of different contact materials and to the oxidation of the aluminum. The aluminum terminal to the aluminum wire shows an initial rapid increase in resistance, because of the rapid formation of relatively high-resistance aluminum oxide. However, the rate of aluminum-oxide formation decreases as a protective coating is formed on the wire, thus giving somewhat greater resistance stability after eight days of the corrosion test. The greatest resistance stability is obtained with the treated terminal and aluminum wire, since in this case galvanic action is eliminated, and the chemical corrosion stability has been increased.

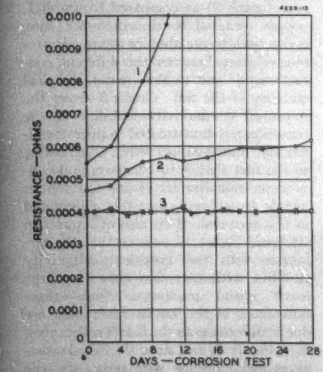


Figure 13. Electrical resistance—corrosion time of different contact metals—tinned copper wire

The Effect of Temperature During the Corrosion Cycle

The curves in Figure 15 give the relative conductivity stability of different types of terminals when subjected to a corrosion cycle consisting of salt spray alternating with circulating-air oven at various temperatures. The graphs marked *A* are the results obtained using tinned-copper terminals with tinned-copper wire; the graphs marked *B* are corrosion-resistant-treated terminals with tinned-copper wire. The temperatures used with the tinned-copper terminals and wire are 25, 66, 100, 133, 166, and 200 degrees centigrade. The temperatures used with the corrosion-resistant-treated terminals were 100, 133, and 166 degrees centigrade. These results were obtained with number-22-16 terminals and seven-strand number-18 wire with the terminals mounted back to back as shown in Figure 6. The resistance in ohms in Figure 15 is indicated by R_1 in Figure 7 and includes portions of each lug plus two crimps plus five-eighths inch of wire. The corrosion cycle consisted of eight hours of four per cent salt spray

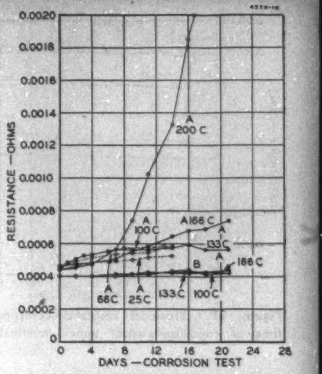


Figure 15. Electrical resistance—corrosion-time effect of different temperatures

followed by 16 hours in a circulating-air oven at the temperatures indicated. The results of electrical-resistance measurements as a function of corrosion time show very good stability at all temperatures for the corrosion-resistant-treated terminals. For the tinned-copper terminals, the conductivity stability is satisfactory for all temperatures, except the highest ones. The effects of the high temperature are both an increase in the corrosion rate, and the formation of oxides having relatively high specific resistance.

Conclusions

1. Solderless terminals may be designed to be both chemically and electrically stable under corrosion conditions of salt spray and heat. It is believed that these corrosion conditions represent reasonably severe operating conditions.

2. The contact metals should have maximum chemical corrosion stability and a minimum electropotential between them for improved performance.

3. The tensile strength of the stranded wire to the crimped joint of the solderless terminal may be made approximately equal to that of the stranded wire when terminated in a solderless terminal.

4. The electrical resistance of the solderless terminal is independent of the magnitude of the current. Tests made on number-18 American Wire Gauge tinned-copper stranded wire with corresponding solderless terminal gave electrical resistance independent of the current over the range from ten microamperes to ten amperes at both room temperature and 100 degrees centigrade.

5. The electrical resistance of the solderless terminal is less than that for an equal length of the corresponding stranded wire. This should insure satisfactory operating performance with respect to temperature rise under load.

Electrical Control in Automatic Pilots

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Synopsis: Engineers generally have been encouraged to attack new seemingly difficult and complicated problems by adapting the general principles utilized in their peacetime work to specific situations arising from the changed methods of modern warfare. This is well exemplified in the solution of aircraft-automatic-control problems.

A summary of automatic-pilot principles and a description of some of the unique and less understood features of a specific modern design are discussed in this paper. It is of especial interest at the present time, because many manual operations of flight and engine control are being studied with a view to making them automatic, and, because as this trend becomes more pronounced, the interconnection of these automatic features will make the problems of each interrelated.

THE automatic pilot is, as its name implies, a mechanism capable of automatically piloting an aircraft and maintaining it on a course, despite disturbances in the surrounding air.[1] Such terms as "relief pilots," "maneuvering pilots," "hard or soft pilots," are used to classify apparatus which accomplishes this result. Relief pilots are intended to relieve the strain on the human pilot mainly during straight level flight and are more simple than the maneuvering type of pilot. Hard pilots are designed to hold a given course or attitude rigidly without consideration for the comfort of the passengers and crew. The soft pilot, on the other hand, holds the general course and attitude but without uncomfortably jarring the personnel. Some designs of automatic pilots incorporate all the features of relief, maneuvering, and hard or soft control.

It is highly desirable to have the automatic pilot under the control of the human pilot at all times, so that it serves as his assistant to relieve him of the routine operations of flying. He is thus able to devote more attention to other problems, such as engine control and aerial navigation. The advantage of relieving the human pilot in this manner has been emphasized in the larger airplanes where increased personnel have been required despite the additional operations already made automatic. As more of the duties are performed by an "automatic crew" under human guidance, the human crew will perform its work more proficiently and with less fatigue.

There are a number of requirements which an automatic pilot must meet in order to be considered satisfactory. Primarily it must hold any set course and attitude, within the limits of the aircraft performance, for periods suitable to the navigational problems involved. In accomplishing this it must be stable. It must neither cause the control surfaces to flutter nor create hunting of the aircraft of a magnitude that would be noticeable to a passenger. Ease of operation, both in turning the pilot "off" and "on" and in changing course or attitude, is an important factor to the human pilot. Ease of overhaul and repair is equally important to the maintenance crew. As is the case with all equipment for aircraft, light weight and small size are essential, especially in parts mounted on the instrument panel. The automatic pilot should "fail safe," that is, failure of any of its components should not result in violent motion of the airplane. In addition, the automatic pilot must be disconnected easily and overpowered readily.

Figure 1. A gyroscope tends to maintain a fixed direction in space

The fundamental operation of an automatic pilot is relatively simple. Basically its operation is analogous to that of a human pilot. When an error in the course or attitude of the plane is detected, both the human pilot and automatic pilot move the control surfaces in such a way as to reduce this error and, so that the resulting motion of the aircraft is stable; that is, correction of course and attitude errors is accomplished smoothly and without overshooting.

Detection of an error in course or attitude requires a reference. Gyroscopes are used almost universally as references for automatic pilots, since they tend to maintain a fixed direction in space, as shown in Figure 1. They also may be used as references by the human pilot when the ground is not visible. Course and attitude errors may be determined by measuring displacement of the airplane with respect to these gyroscopic references. The measuring devices which are known as error detectors or pickoff units correspond to the senses of a human pilot. The signal from the pickoff unit is modified in the proper manner to achieve stability, amplified, and then transmitted to the control surfaces by means of a servomotor. As shown in the appendix, stable operation of the aircraft requires that the motion of the control surface should be responsive to the velocity, and in most cases the acceleration of the airplane in addition to being responsive to the error signal, that is, anticipation of the airplane's future position, is required if stability is to be achieved.[2,3]

Automatic-Pilot-System Components

In conventional automatic-pilot practice the reference units are usually a directional gyroscope, as shown in Figure 2, with its spin axis horizontal for course reference and a horizon gyroscope, as shown in Figure 3, with its spin axis vertical for the pitch and bank references. The directional gyroscope is subject to random drift due to friction present in the unit as well as drift caused by the rotation of the earth. Consequently it is compared normally at periodic intervals with a magnetic compass and reset if necessary. It is possible, however, to couple the directional gyroscope to a magnetic compass so that it is reset continuously and automatically. A magnetic compass is not normally used for a course reference since it is seriously affected by pitching and rolling of the aircraft. However, if a gyroscope with a vertical spin axis is used to maintain the compass in a horizontal plane, it may be used directly as a course reference.

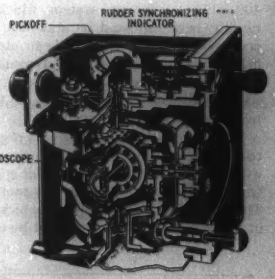

Figure 2. Cutaway view of a directional gyroscopic control instrument

The horizon gyroscope is subject to drift of the same type as that in the directional gyroscope. In this case, however, a pendulous erection system, the average direction of which is the true vertical, is used to correct the instrument.

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The speed of this correction must be sufficiently high to correct for the earth's rotation with a negligible error, but, because of the centrifugal effects on the pendulum during turns, there is an upper limit to the speed at which correction may be applied.

Gyroscopes may be of the air-driven or electrically driven type. The electrically driven units provide better performance at high altitudes, better starting characteristics at low temperatures, and a reduction of the dirt hazard in the instrument. The recent developments of electric gyroscope motors[4] of instrument size has made it practical to mount electrical gyroscopes on the instrument panel, thus utilizing them as flight instruments

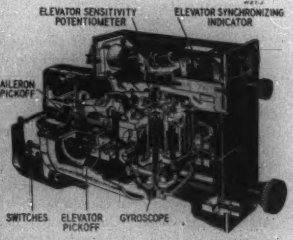

Figure 3. Cutaway view of a bank-and-climb gyroscopic control instrument

as well as the references for the automatic pilot. In these small gyroscopes a-c motors of the squirrel-cage or hysteresis type are preferred to d-c motors because of the elimination of brush-wear and radio-interference problems, as well as the ease of attaining higher speeds. The 400-cycle a-c power system which is rapidly being adopted as standard aircraft power makes it possible to obtain high gyroscopic speeds and a resulting high angular momentum of the gyroscope with conventional four- or two-pole motors of the a-c type.

The motion of the airplane with respect to these references is normally measured with a pickoff unit which provides a control signal proportional to this motion. The older mechanical or air-valve pickoffs in many cases are being replaced by electrical units which may be classified as the direct-contact or potentiometer type, the variable-inductance or E type, and the induction-regulator or Selsyn type. In general, these units are oriented so as to produce an a-c signal, the polarity and magnitude of which correspond to the direction and amount of deviation of the airplane. Typical output voltage characteristics of the induction type are shown in Figure 4.

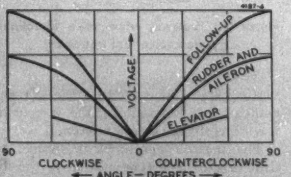

Figure 4. Output voltage characteristic of electrical pick-off and follow-up units of the induction (Selsyn) type

Some of the stabilizing or antihunt signal sources which have been used are as follows:

(*a*). Restrained or rate gyroscopes, if properly oriented, will provide a displacement having a magnitude proportional to the angular velocity of the aircraft about the axis being stabilized.

(*b*). A signal proportional to the position of the control surface or the force on it will contain both acceleration and velocity components of the motion of the aircraft and may be used for stabilization.

(*c*). Accelerometers may be used to obtain acceleration components of the aircraft motion.

(*d*). Various aerodynamic measurements, such as wing-tip velocities, rate of climb, angle of attack, and lift on the wings have been used for stabilizing purposes.

(*e*). The error signal may be operated on directly to obtain derivative components. If this signal is electrical it is possible to perform this operation by means of conventional capacitor-resistance networks.

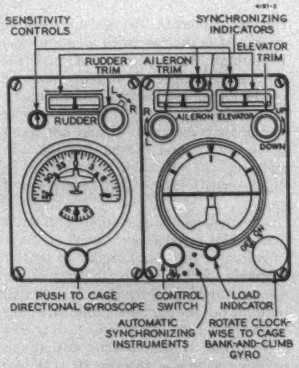

Figure 5. The control knobs combined on the instrument panel of a relief pilot

The problem of automatic stabilization of an aircraft is complicated somewhat by the fact that the system parameters, in particular the inertia, damping constants, and the response of the aircraft to control surface motion vary with loading, altitude, air speed, and so forth. Although it is true that there is considerable interaction between the various axes of an aircraft, particularly the roll and yaw, it has been found that satisfactory relief pilots can be built without taking account of this interaction.

The power units or servomotors for operating the control cables may be classified according to their power source

Past experience with the pneumatic piston type of servomotor has demonstrated that they are operable, but that it is more difficult to stabilize the aircraft because of the compressibility effects in the servomotor.

The hydraulic piston servomotor eliminates these compressibility effects and provides an easily controlled source of power; low-pressure units similar to those shown in Figure 10 are in common use today. These units generally are provided with a by-pass valve for hydraulic disengagement during manual flight. In order to permit the human pilot to take over control in case of an emergency, relief or overpower valves are placed across the piston.

Electric servomotors are usually high speed, of either the a-c or d-c type, driving through a gear reduction to an output pulley. The use of this type of servomotor has been limited somewhat by the relatively high inertia to torque ratio which introduces a time delay, the weight of the control equipment required to obtain variable speed operation, and the complexity of the mechanical disengagement necessary for manual flight. Motors have been designed specially to reduce the inertia to torque ratio; in other instances the motor has been allowed to run continuously, and the load has been controlled by clutching. Saturable reactors also have been used to control the speed of low-power a-c servomotors. Disengagement is usually accomplished by means of solenoid-operated clutches.

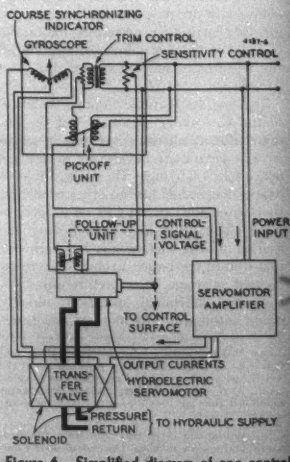

Figure 6. Simplified diagram of one control channel of a relief pilot

The type of amplifier units will depend upon the type of pickoff and servomotor used. For a system using an air-valve pickoff and a pneumatic or hydraulic power servomotor, the fluid flow to the cylinder is controlled by a balanced valve which is actuated by a vacuum-operated diaphragm. The differential vacuum on this diaphragm is controlled by the air-valve pickoffs in the gyroscope. At high altitude, because of the reduction of atmospheric pressure, the force available on the valve is reduced, resulting in reduced velocity of the servomotor.

With an electrical pickoff an electronic amplifier is usually used, first, to discriminate the polarity of the incoming signal, and second, to amplify it to a higher-power level. When this amplifier is used to control an electric servomotor, additional control means, such as saturable reactors or solenoid-operated clutches, are used. Hydraulic servomotor units are controlled conveniently

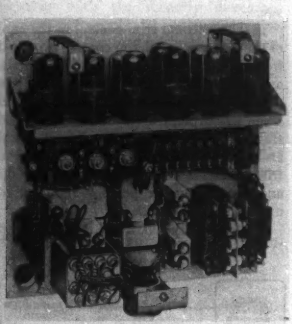

Figure 7. Servomotor amplifier with cover removed

by means of a solenoid-operated balanced oil valve.

Adjustment of the course and attitude of the airplane during automatic-pilot flight, as well as alignment of the automatic pilot with the airplane before engagement, requires controls readily accessible to the pilot. A change in course or attitude of the airplane is usually accomplished by introducing a trim signal into the control circuit, thereby requiring that the airplane change its attitude to restore equilibrium. This trim signal may be introduced mechanically by displacing the rotor of the pickoff with respect to the stator, by electrically displacing the stator signal by means of a selsyn system, or electrically by introducing a bias voltage. It is also desirable to have control of the damping action of the pilot as well as the control switches readily available. In the maneuvering type of pilot the turn and bank controls are combined, so that motion of one control will introduce a rate of turn with the correct amount of bank.

A Typical Autopilot With Electrical Control

The automatic pilot described in detail in this paper exemplifies the basic features of automatic pilots and also illustrates the trend toward electrification of many of its parts. It is a modern design developed specifically as a relief auto-

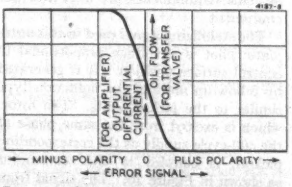

Figure 8. Servomotor amplifier characteristic curves

matic pilot and intended mainly for straight level flight, although capable of performing simple maneuvers. It incorporates recent developments in small electric gyroscopic flight instruments and has fulfilled the need for an automatic pilot having the advantages of electro-hydraulic operation. Its panel mounting dimensions are interchangeable with those of older designs. A simplified diagram of one channel of the system is shown in Figure 6.

The gyroscope references contain small hysteresis-type motors running at a synchronous speed of 12,000 rpm from a 115-volt 400-cycle 3-phase supply. The rotor weight running outside the stator provides exceptionally high gyroscopic stabilizing torques. Figure 2 shows this

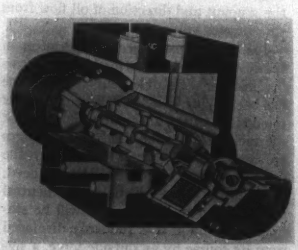

Figure 9. A cutaway view of a solenoid-operated transfer valve

motor mounted in gimbals and geared to a vertical dial for use as a directional flight indicator.

The pickoff units are of the induction type having rotors excited directly from a single phase of the 400-cycle supply and stators wound single phase from which the signals are taken. The rotor of the directional pickoff is mounted on the gyroscopic vertical axis, and the stator of this unit is mounted on the frame. Consequently, there is no mechanical friction imposed on the gyroscope by the pickoff unit, since the rotor excitation is already available on the gimbal for motor power. The stator of the pickoff unit is mounted in a ring gear and driven by the knob on the front panel so as to provide a simple means for changing course while in automatic flight.

Figure 3 shows the arrangement of a similar motor used for the bank and climb control. The spin axis is nearly vertical, and a unique electrical erecting device properly damped[8] and actuated by gravity holds it in this position. During turns the centrifugal force acting on the erecting device may cause a slight drift from its correct position. However, a backward tilt of the gyroscopic spin axis has been introduced to compensate correctly for this effect at a rate of turn of approximately 180 degrees per minute. At other rates of turn the compensation is only approximate.

The aileron pickoff unit is mounted

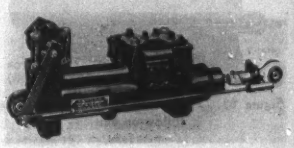

Figure 10. A hydraulic servomotor with an electrical follow-up unit coupled to it

with its primary winding on the main gimbal and its secondary winding on the frame. The elevator pickoff is mounted with its primary winding on the horizon bar linkage, so that it moves with the motor and has its secondary winding on the main gimbal. Typical output voltages from the pickoffs for various angles of deviation are shown in Figure 4.

The secondary windings of the aileron and elevator pickoffs are not rotated easily from outside the gyroscope, so that potentiometer trim controls are added with knobs, as shown in Figure 5, and with connections, as shown in Figure 6.

The compactness and light weight of this pilot result in part from mounting all the controls, with the exception of the "on–off" oil valve, directly on the face of the gyroscope. Separate sensitivity control knobs are provided for rudder-, aileron-, and elevator-damping adjustment. Their electrical connections are shown in Figure 6, and the arrangement of the controls is shown in Figure 5. Small synchronizing instruments are provided in the gyroscopic cases to indicate when the trim knobs are correctly set to

hold the course and attitude that the plane is flying. These instruments read zero when the currents through the transfer-valve solenoids are balanced.

The electric control switch for the automatic pilot is mounted in the lower left-hand corner of the bank and climb gyroscope. It has positions for:

(a). The use of the gyroscopes only as flight instruments.

(b). The use of the synchronizing indicators for "trimming" the automatic pilot before engagement.

(c). The use of all the components in automatic flight.

In addition to these control knobs, the normal caging and dial adjusting knobs of flight indicating instruments are provided.

The control signals for the rudder, aileron, and elevator functions are fed into three separate amplifier channels in the servomotor amplifier shown in Figure 7. The purpose of the amplifier is to convert the low-level a-c signal input to d-c output of sufficient power to operate the solenoids of the hydraulic transfer valve. Essentially, each channel consists of a balanced two-stage amplifier connected so that the first stage is responsive to the polarity and magnitude of the incoming signal, and the second stage is the power amplifier. With no input signal the output currents of each half of the channel are balanced. With an applied signal the current in one half of the channel will rise, and that in the other half will fall in an amount proportional to the signal voltage; if the signal polarity is reversed the effect on the output current is reversed. The form of the output current versus input signal curve is shown in Figure 8.

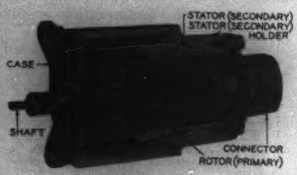

Figure 11. A cutaway view of an electrical follow-up unit

The transfer valve shown in Figure 9 is actuated by the output of the servomotor amplifier, and consists of three hydraulically balanced oil valves, each valve being positioned by proportional solenoids located at each end. These solenoids have armatures suspended in radial air gaps without bearings and are spring biased outwardly in the axial direction from their magnetic centers. Differential excitation of the solenoids produces an axial motion of the armatures which operates the valve. These units have been designed so that the rate of oil flow from the valve is approximately proportional to the differential current through the solenoids. This characteristic, together with the linear electronic amplifier characteristic, results in a servomotor velocity approximately proportional to the input signal up to the saturation limit of the amplifier. The arrangement of solenoids at both ends of each valve insures that the valve will fail safe, that is, return to neutral if the electric signal is removed. Conventional hydraulic servomotor units, of a size dictated by the airplane requirements, are used with this equipment.

The stabilizing signal used in this automatic pilot is a voltage proportional to control surface position. It is generated by follow-up units of the induction type similar to the pickoff units. The rotor, which is excited from the same phase of the 400-cycle supply as the corresponding pickoff, is coupled to the servomotor as shown in Figure 10. The signal from the stator of this unit is connected in series with the pickoff signal before it enters the amplifier. The sinusoidal voltage output characteristic of this unit, as shown in Figure 4, is modified by the nonlinear crank-arm coupling, so as to produce an output voltage essentially proportional to the servomotor piston displacement. A cutaway view of this electrical follow-up unit is shown in Figure 11.

Thus the control-signal voltage entering each amplifier channel is the resultant of three components: the trim control voltage for manually setting the attitude of the plane, the pickoff voltage indicating the deviation of the airplane from the set attitude, and follow-up voltage indicating the deflection of the control surface from its neutral position. The resultant input signal determines the amount and direction of unbalance in the output currents and, consequently, the amount and direction of oil flow from the transfer valve.

The typical sequence of operation of the system may be described in the following manner. Assume that the airplane has been flying in a straight course under the control of the automatic pilot so that the pickoff, follow-up, and trim voltages are zero. Under these conditions the amplifier output currents will be balanced, the transfer valve will be in the neutral position, and the servomotor will be stationary. Now if it is suddenly displaced from its course by an outside force, a signal immediately appears on the gyroscope pickoff thereby disturbing the resultant zero-voltage balance of the amplifier input signal. The resulting plate current unbalance in the power tubes of the amplifier causes the proportional oil valve to move from its neutral position thereby permitting oil flow to the servomotor. The servomotor then moves the control surface in the proper direction to return the airplane to its original course. As soon as the control surface moves, a voltage proportional to the amount of this movement is induced in the stator of the follow-up unit. This voltage opposes the voltage induced in the gyroscope pickoff and so reduces the current unbalance from the power amplifier as well as the displacement of the proportional valve. Consequently, motion of the control surfaces continues until these voltages are equal and opposite. At the same time, however, the displacement of the control surface causes the airplane to return gradually to its original course, thereby gradually reducing the pickoff voltage to zero. This reversal of input signal polarity reverses the oil flow to the servomotor, and so the control surface gradually returns to its neutral position. System equilibrium is again established when the control surface is in the neutral position with zero follow-up voltage and when the airplane is set at the correct attitude with zero gyroscope pickoff voltage.

If the electrical trim control in the case of the elevator or aileron control is moved from its neutral position thereby unbalancing the zero signal input voltage, the new equilibrium point will be reached when the airplane attitude has shifted, so that the gyroscope pickoff voltage is equal and opposite to those introduced by the trim control setting and the new follow-up and control surface position required to maintain this attitude.

If the sensitivity control is adjusted so that the follow-up excitation is decreased, the follow-up signal gradient is reduced, and the control surface must move a greater distance to balance out the pickoff signal. This results in a "stiffer" pilot control.

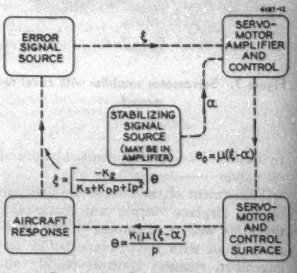
ERROR SIGNAL SOURCE
ξ
SERVO-MOTOR AMPLIFIER AND CONTROL
α
STABILIZING SIGNAL SOURCE (MAY BE IN AMPLIFIER)
$e_0 = \mu(\xi - \alpha)$
$\xi = \left[\frac{-K_2}{K_3 + K_0 p + Ip^2}\right]\theta$
AIRCRAFT RESPONSE
$\theta = \frac{K_1 \mu (\xi - \alpha)}{p}$
SERVO-MOTOR AND CONTROL SURFACE

Figure 12. Servomotor system

Samples of this automatic pilot have been used in tests to stabilize airplanes at various altitudes and flying speeds with the indication that the sensitivity control knobs can be set on the ground to a satisfactory position for most normal flying conditions. The stabilization of the airplane as well as the direction held were

found to be well within the desirable limits for this type of automatic pilot.

Conclusions

Automatic pilots are one step toward achieving complete automatic controls for aircraft. This step as a separate problem has been solved satisfactorily in a number of ways that are in general use. One of the major advances in the art has been brought about by the electrification of several components for the automatic pilot, including the gyroscope motors, the error signal pickoff, the follow-up units, and the amplifying units including the transfer valve. These have resulted in better starting characteristics, in more satisfactory operation at high altitude, and in the elimination of mechanical linkages to the instrument panel. The electrical pickoff and follow-up signals have made possible electrical trim controls for adjusting the stability of the aircraft. The use of small potentiometers, together with the recently developed electric gyroscopes of instrument size, allow all of the controls with the exception of the "on–off" oil valve to be mounted on the instrument panel directly in front of the human pilot. The automatic pilot described in detail characterizes all the aforementioned features. Flight-test results have proved the superiority of this design as a relief type of automatic pilot.

Appendix. Theory of Automatic-Pilot Operation

The mathematical study of automatically controlled flight is sufficiently complex to warrant an entire paper. Consequently, only a descriptive analysis will be presented to provide a better understanding of the functions of the various components.

Assume that there is no mutual effect among the three controlled axes, and that the problem of stability is concerned only with small angular deviations. One control axis of the pilot then may be represented schematically by the servomotor system shown in Figure 12.

The component parts may be any of the types mentioned in the paper. When an electrical pickoff is used its time constant is practically zero, and its output can be represented by ξ where ξ is proportional to the error angle.

The stabilizing signal source usually has a small time constant, and its output can be represented by α.

The input to the amplifier is $\xi-\alpha$, and if μ is the amplification the output is $\mu(\xi-\alpha)$. Although the time constants of amplifiers are greater than those of the signal devices, they are negligible compared with those of the airplane in the case of electronic amplifiers followed by solenoid-operated transfer valves.

$$e_0=\mu(\xi-\alpha) \tag{1}$$

This output signal is connected to the servomotor to cause it to move at a rate proportional to the signal. A time constant will appear in the servomotor response, but again this is usually negligible so that if θ is the servomotor and control surface position tending to correct ξ,

$$p\theta=K_1\mu(\xi-\alpha) \tag{2}$$

where K_1 is the servomotor constant.

The displacement of the control surface, θ, from its neutral point produces an approximately proportional torque about the center of gravity of the airplane, so that the airplane accelerates in a direction to decrease ξ. The resulting angular velocity, however, gives rise to damping and static stability torques which limit the maximum velocity This is the major time constant in the system and consequently cannot be neglected. The response of the airplane to control surface motion then may be expressed as:

$$K_2\theta=-K_s\xi-K_Dp\xi-Ip^2\xi \tag{3}$$

where:

K_s = static stability constant
K_2 = control surface constant
K_D = damping constant
I = angular inertia of plane

If equations 2 and 3 are solved simultaneously, there is obtained:

$$\left[p^3+\frac{K_D}{I}p^2+\frac{K_s}{I}p+\frac{K_1K_2}{I}\mu\right]\xi-\frac{K_1K_2\mu}{I}\alpha=0 \tag{4}$$

With the airplane constants normally encountered in control work and the system gain, $K_1K_2\mu$, required for reasonable accuracy of flight, a stable solution of equation 4 requires that the last term be present in the correct amount. Generally, this term will be of the form:

$$\frac{K_1K_2\mu}{I}\alpha=\frac{K_1K_2\mu}{I}(-Ap-Bp^2)\xi \tag{5}$$

so that equation 4 becomes:

$$\left[p^3+\left(\frac{K_D}{I}+\frac{BK_1K_2\mu}{I}\right)p^2+\left(\frac{K_s}{I}+\frac{AK_1K_2\mu}{I}\right)p+\frac{K_1K_2\mu}{I}\right]\xi=0 \tag{6}$$

By a proper choice of the constants B and A the solution of this expression will be damped properly so as to provide stable operation of the airplane. The constants B and A determine, respectively, the magnitudes of the acceleration and velocity components of airplane motion, $p^2\xi$ and $p\xi$, which are used for stabilization. Various means have been used to obtain these components, but perhaps the most convenient and widely used method is to feed back into the amplifier a signal proportional to the position of the control surface. In this case:

$$\alpha=K_3\theta \tag{7}$$

where K_3 is the feed-back constant.

If equations 7 and 3 are solved simultaneously, there is obtained:

$$\alpha=-\frac{K_3K_s}{K_2}\xi-\frac{K_3K_D}{K_2}p\xi-\frac{K_3I}{K_2}p^2\xi \tag{8}$$

If equation 8 is substituted in equation 4, the equation of motion is:

$$\left[p^3+\left(\frac{K_D}{I}+K_1K_2\mu\right)p^2+\left(\frac{K_s}{I}+\frac{K_1K_2K_D}{I}\right)p+\frac{K_1K_2K_3\mu}{I}+\frac{K_1K_2\mu}{I}\right]\xi=0 \tag{9}$$

Proper stability adjustment is now obtained by adjusting K_3. If the control-surface position is obtained as an electrical signal, K_3 then may be varied easily so as to obtain the desired stiffness of control and flight characteristics for various types of airplanes.

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Peak Voltages With D-C Arc Interruption for Aircraft

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DURING the interruption of direct currents in circuits having inductance, the presence of high-voltage peaks or "inductive kicks" is quite commonly recognized in a qualitative sense. There is however little quantitative data on this subject, particularly at the voltages, loads, and altitudes encountered on modern aircraft.

Data on inductive voltages usually are obtained by taking cathode-ray oscillograms or by observing a cathode-ray oscilloscope. The former method is accurate but relatively slow and tedious; the latter, with the tubes available up to this time, has been somewhat questionable because of the difficulty of clearly determining by eye a single fast transient. In this investigation use has been made of a cathode-ray tube with a retentive screen—so retentive that the trace of a single half-cycle sweep of a 60-cycle wave takes several seconds to disappear. Using this tube it has been possible to take a large amount of data in a short time, so that, instead of relying on a few oscillograms, ten readings could be taken at each point and an average and range established for the voltage disturbances set up.

Scope of This Paper

It is the purpose of this paper to present experimental data on the magnitude and variations of voltage peaks set up by d-c arc interruptions of inductive circuits. These voltages were measured on d-c systems of 30, 60, 125, and 250 volts with currents ranging from 0.1 to 220 amperes and simulated altitudes from sea level to 50,000 feet. The loads used included typical aircraft devices such as motor fields and contactor coils.

The effect of the induced-voltage peaks on insulation puncture or flashover was not investigated. This phase of the subject requires a separate investigation.

Because of limits in time, no attempt is made to explain theoretically the results obtained. Rather, emphasis is on the presentation of data taken to date. An investigation was made, at the same time, of the interrupting ability and the arc time of some of the devices used in these tests, and the results are presented in an accompanying paper by Quill and Rader.[1]

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VIRGEL E. PHILLIPS and WALTER P. MITCHEL, both now in the Armed Forces, were employed in the industrial-control engineering division of General Electric Company, Schenectady, N. Y., at the time this paper was written.

Summary

The data presented may be summarized as follows:

1. When a Switchette (the trade name for a small double-break switch with 0.020-inch gaps and opening time of one to two milliseconds) was used on 250 volts and 0.4 ampere at sea level, voltage peaks as high as 28 times line voltage or 7,000 volts were observed.

2. A maximum peak of 130 times line voltage or 3,900 volts was observed while operating the Switchette double-break on 30 volts and 0.4 ampere at sea level.

3. When the Switchette was used the voltage peaks were found to decrease with altitude for all voltages tested. A maximum of seven to one in ratio of voltage at sea level to voltage at 50,000 feet was observed.

4. Using a double-break contactor which has a $^{5}/_{16}$-inch gap per break and a gap-travel time of 12 milliseconds, the induced voltage peaks rise with altitude in every case. A maximum of two to one in the ratio of voltage at 50,000 feet to voltage at sea level was observed. The loads on which these tests were made, as the text of the paper will show, were very much less inductive than those used for the Switchette.

5. Variations of humidity over a wide range has little effect on the voltage peaks at any altitude.

6. There are no voltage peaks above normal line voltage in a purely resistive circuit. For interruptions which take place in circuits having the same system voltage and the same initial current, the more highly inductive circuits caused the higher-voltage peaks.

7. For any particular voltage lower currents in general give higher peaks. An exception was noted with the Switchette where peak voltage increased as current was reduced down to about 0.4 ampere. A further decrease in current gave a reduction in voltage.

8. For the same voltage and current, peak voltages occurring for double break on the Switchette were as much as 190 per cent of the single-break peak.

9. The breakdown potential of one-fourth-inch-diameter brass electrodes with altitude is shown in Figure 3 of the paper, "Potential Breakdown of Small Gaps Under Simulated High-Altitude Conditions."[1] For an air gap of $^{1}/_{32}$ inch the breakdown voltage was 4,000 volts at sea level and 1,000 volts at 50,000 feet altitude. Peak voltages higher than those were found in this investigation, indicating the possibility of damage to insulation due to surface flashover such as might occur in an *AN* connector.

10. Frequencies in the order of 50,000 cycles per second were encountered, usually occurring at low currents and at high altitudes. This is a possible source of interference for radio equipment in the immediate vicinity.

Fundamentals of D-C Interruption

The important factors contributing to the current-interrupting ability of a switch in air are the material of the contacts, the contact configuration, the speed with which the contacts open, the final gap length, the condition of the air, and the constants of the electric circuit itself.

If the circuit contains inductance as well as resistance, as it usually does, interruption will result in high voltages

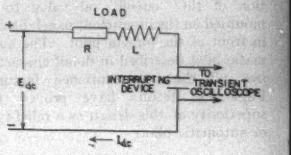

Figure 1. Elementary diagram of test circuit

across the contact tips. Consideration of the interruption on the basis of energy reveals two sources of energy, that stored in the inductance and that supplied by the source of power during the interrupting period. The total energy must be dissipated in the resistance of the circuit and in the arc itself. When the tips first part, an arc will be struck, and hence a low arc voltage will appear. Current will decrease as the gap between tips increases until at some low value it suddenly will go to zero or very nearly so. This last sudden change of current causes a high voltage to be induced across the inductance due to Ldi/dt, and this also must appear across the contacts. This voltage may be enough to cause the gap to break down again with a corresponding decrease in voltage to the arc voltage for that particular gap opening. There may be several of these breakdowns, or, on the other hand, the rate of recovery of the dielectric strength of the air may be faster than the first rise in voltage, and hence an interruption will occur on the first attempt. If the current goes to zero, the voltage across the contacts must fall from the peak value to line voltage immediately.

However, indications are that in an appreciable number of cases the current

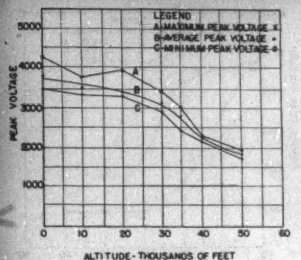

Figure 2. Peak-voltage distribution versus altitude resulting from interruption of an inductive load of 0.4 ampere at 30 volts direct current with the double-break Switchette

Gap: 0.020 inch per break. Ten consecutive readings were taken, and the average, maximum, and minimum readings are shown. Load: inductive *A*, Table I, 0.4 ampere—four coils in parallel

drops suddenly from normal arc current to a very low current which may continue for some time. Thus voltage across the contacts in this case would not fall rapidly from the peak value down to line voltage, but rather only to some intermediate value, and then slowly approach line voltage. This phenomenon is similar to that of the normal and abnormal glow periods as described by Slepian.[3] Also, the glow period following the peak has been noted by the authors in the experimental tests. One common form was for the voltage to drop from the peak down to 300–500 volts and remain for periods of the order of one millisecond, and then taper off to line voltage.

Although the initial conditions of voltage and current are the same before each opening, arc characteristics and peak voltage may differ widely on successive interruptions. Some causes for these variations may be: variations in opening speed, variations in air conditions and the amount of convection action on the arc, and irregularities in the contact surface causing the arc to strike at different points on the contact.

Gap opening except in a limited way and opening speed are factors in the peak voltage reached, but this investigation did not cover these variables. In general, to prevent excessively high peak voltages, a d-c contactor that opens rapidly should not open too wide.[4]

Test Equipment and Procedure

In the measurement of the peak voltages, use was made of a new transient oscilloscope and associated circuit developed in the industrial-control engineering division of the General Electric Company. Its main feature is a high-voltage electronic tube, similar in shape and size to that used in the cathode-ray oscillograph, but having a highly persistent fluorescent screen which allows it to retain the trace of a single transient long enough to be observed by the eye. Thus peaks are read quite easily and accurately, and the wave shape on each interruption can be observed. A resistance–capacitance voltage divider designed to operate independently of the frequency over the range of frequencies involved was used. Every effort was made to keep the leads short and the relative location of the equipment such as to minimize any pickup caused by the high-frequency oscillations at interruption.

The general form of the test circuit is shown in Figure 1. The circuit-interrupting device was placed in a sealed bell jar which could be evacuated. Leads were brought out through sealed terminals at the bottom. The effect of altitude was simulated by reducing the pressure within the bell jar, no attempt being made to control either humidity or temperature. The conversion of pressure to elevation was based on data from National Advisory Committee of Aeronautics report 218.

For the high-humidity test a container of water with an electric-heater attachment was placed within the bell jar and left until water was condensing out around the bottom and on the jar itself. Thus a humidity approaching 100 per cent was attained and held for the duration of this run.

All the data presented in this paper were taken on the following two devices:

1. An aircraft switch known as the Switchette. This is a small double-break switch rated at ten amperes, single circuit, 30 volts, inductive load at all altitudes. It has silver tips of one-eighth-inch diameter and a gap of 0.020 inch. Single-break data were taken using this same Switchette with one contact blocked closed. Hereafter this device will be designated as Switchette single-break or Switchette double-break.

2. A double-break switch with a bridge-type movable contact arm carrying silver tips about one-half-inch diameter on seven-eighths-inch centers. The tip gap was set at 0.312 inch. This unit was a part of a commercial size-1 contactor (*CR*2810–1811) having a tip rating on alternating current of 25 amperes and a motor rating of $7\frac{1}{2}$ horsepower at 550 volts. Hereafter this device will be designated as the double-break contactor.

The loads used are listed in Table I. The inductances given are differential inductances[5] calculated from magnetic oscillograms of current build-up. They serve the purpose of providing a basis of comparison of inductances and hence some indication of the severity of the peak voltages. However, these values should not be accepted as those to use in calculations, as inductance is not a constant but rather a function of the current and rate of change of current for iron-core coils. For example, inductive *A* shows 55 henrys at 50 per cent current and 8 henrys at 100 per cent current. Also

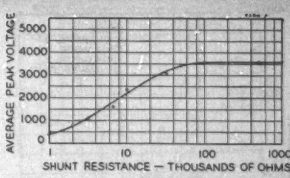

Figure 3. Average peak voltage versus resistance shunted across contacts resulting from the interruption of an inductive load of 0.4 ampere at 30 volts direct current with a double-break Switchette at sea level

Gap: 0.020 inch per break. The average is taken for ten consecutive readings. Load: inductive *A*, Table I, 0.4 ampere—four coils in parallel

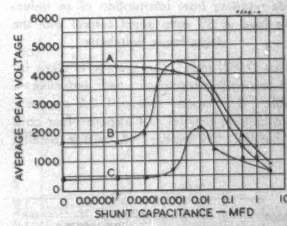

Figure 4. Average peak voltage versus capacitance shunted across contacts resulting from the interruption of an inductive load of 0.2 and 0.4 ampere at 125 volts with a single-break Switchette

Gap: 0.020 inch. The average is taken for ten consecutive readings. Load: inductive *A*, Table I, 0.2 ampere—two coils in series, 0.4 ampere—one coil

A—0.2 ampere—0 feet •
B—0.4 ampere—0 feet ×
C—0.2 ampere—50,000 feet •

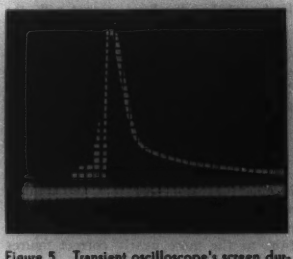

Figure 5. Transient oscilloscope's screen during interruption of an inductive load of 0.2 ampere at 30 volts direct current with the double-break Switchette at sea level

Gap: 0.020 inch per break. Calibration—123 volts per division vertical—one-fourth millisecond per division horizontal. Load: inductive *A*, Table I, 0.2 ampere—two coils in parallel

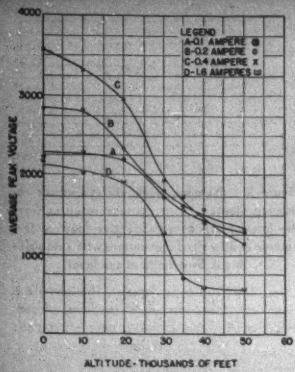

Figure 6. Average peak voltage versus altitude resulting from interruption of an inductive load at 30 volts direct current with the single-break Switchette

Gap: 0.020 inch. The average is taken for ten consecutive readings. Load: inductive *A*, Table I, 0.1 ampere—one coil, 0.2 ampere—two coils in parallel, 0.4 ampere—four coils in parallel, 1.6 ampere—16 coils in parallel

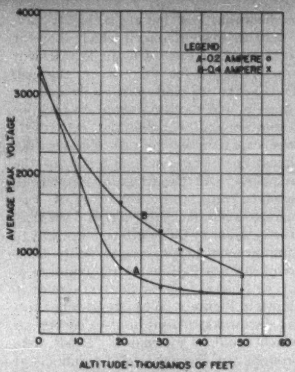

Figure 8. Average peak voltage versus altitude resulting from interruption of an inductive load at 125 volts direct current with the single-break Switchette

Gap: 0.020 inch. The average is taken for ten consecutive readings. Load: inductive *A*, Table I, 0.4 ampere—two coils in series, 0.2 ampere—two coils in series plus external resistance

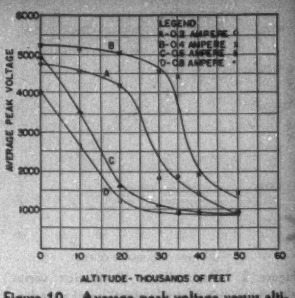

Figure 10. Average peak voltage versus altitude resulting from interruption of an inductive load at 125 volts direct current with the double-break Switchette

Gap: 0.020 inch per break. The average was taken for ten consecutive readings. Load: inductive *A*, Table I, 0.2 ampere—two coils in series. Parallel combinations of above were used for 0.4, 0.6, and 0.8 ampere

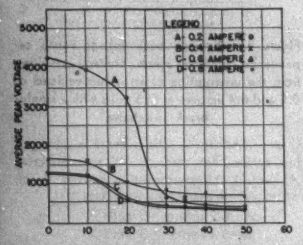

Figure 7. Average peak voltage versus altitude resulting from interruption of an inductive load at 125 volts direct current with the single-break Switchette

Gap: 0.020 inch. The average is taken from ten consecutive readings. Load: inductive *A*, Table I, 0.2 ampere—two coils in series. Parallel combinations of above were used for 0.4, 0.6, and 0.8 ampere

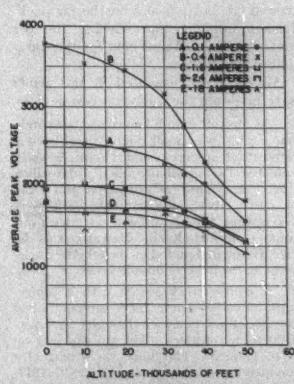

Figure 9. Average peak voltage versus altitude resulting from interruption of an inductive load at 30 volts direct current with the double-break Switchette

Gap: 0.020 inch per break. The average was taken for ten consecutive readings. Load: inductive *A*, Table I, 0.1 ampere—one coil. Parallel combinations of above were used for 0.4, 1.6, and 2.4 amperes. A coil with one-ohm resistance, 360 turns, and 8.5 square inches mean cross-sectional area was used for 18 amperes

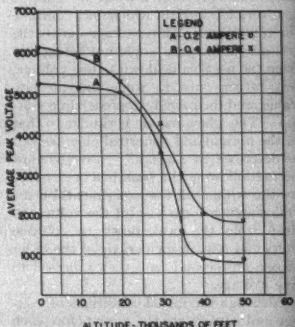

Figure 11. Average peak voltage versus altitude resulting from interruption of an inductive load at 250 volts direct current with the double-break Switchette

Gap: 0.020 inch per break. The average was taken for ten consecutive readings. Load: inductive *A*, Table I, 0.4 ampere—two coils in series, 0.2 ampere—two coils in series plus external resistance

it must be recognized that the inductances found by this method are not the exact values governing current interruption, as the more nearly correct figures would be taken on current decay.

Inductive-*C* load was used for all tests made on the double-break contactor. Current was varied over the range desired by changing a series resistance. Inductive *A* was used for most of the Switchette data. The values shown are for one coil, the desired current at any voltage being obtained by changing the series-parallel combination of these single coils.

As typical aircraft applications inductive-*H*, *J*, and *K* loads were tested. Also used was the shunt field of a one-ninth horsepower aircraft motor, but no inductance figures are given for it.

Data taken previously indicated that peak voltages were higher for a load of a coil with an iron core than for the same coil with an air core. However, peak voltages were much more erratic with the air-core coil, varying as much as two to one on consecutive openings.

Method of Test

The trace on the screen of the transient oscilloscope at each opening of the interrupting device represents the varia-

Table I. Load Inductance

Load Designation	Load	Load Data	Load Rating 100 Per Cent V	Load Rating 100 Per Cent I	Inductance—Henrys at 50 Per Cent I	Inductance—Henrys at 100 Per Cent I
Inductive *A*	Series and series-parallel combinations of d-c industrial relays— data given from each relay	9,600 turns, 1.5-square-inch iron area, Armature sealed	125	0.42	55	8
Inductive *C*	D-c series motor field *MDO*-109 150 horsepower	Series field and commutating field	220	480	0.002	0.0044
Inductive *H*	100-ampere dynamotor contactor coil	2,300 turns, 0.5-square-inch iron area, Armature sealed	28	0.54	2.4	1.5
Inductive *J*	Solenoid-type 200-ampere contactor coil		24	0.42	4.2	1.0
Inductive *K*	Balanced armature-type 100-ampere contactor coil	3,100 turns, 0.09-square-inch iron area, Armature sealed	24	0.19		

tion of voltage across the contacts with time. In taking readings, the contacts were closed long enough to allow the current to reach its steady-state value, and then the maximum voltage across the contacts as they opened was recorded. In all the data presented the peak voltages are the average of ten values taken on ten consecutive interruptions. A typical distribution of these ten readings is shown in Figure 2. The average values have the advantage of giving a more uniform curve. Also, any insulation breakdown due to peak voltages which causes surface flashover and tracking probably will be a gradual result of a large number of high voltages which can be represented best by the average value. Repeat tests taken at a later date indicate that test points can be reproduced within ten per cent.

Effect of Parallel Resistance or Capacitance

An investigation was made of the effect on voltage peaks of resistance or capacitance shunted across the contacts. In Figure 3 is plotted the variation of peak voltage with shunt resistance over a range from 1,000 ohms to one megohm. Above 100,000 ohms, the peaks remained unchanged by an increase in resistance. As the input resistance to the transient oscilloscope is two megohms, it is well above the range at which appreciable suppressing effect is present. This fact is significant when it is recalled that, if a magnetic oscillograph is used to measure arc voltages, resistance must be placed in parallel with the tips of the interrupting device. The magnitude of this shunt resistance is proportional to the system voltage and exerts an appreciable suppressing effect on the peak voltage. Thus a magnetic oscillograph is usually unsatisfactory for measuring peak voltages, even if the frequency response were otherwise satisfactory.

In Figure 4, average peak voltage is plotted against capacitance shunted

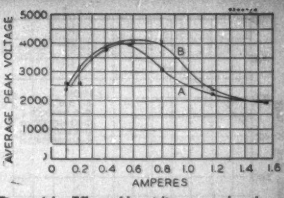

Figure 14. Effect of humidity on peak voltage resulting from interruption of an inductive load at 30 volts direct current with the double-break Switchette at sea level

Load: inductive *A*, Table I
A—Room humidity •
B—High humidity ×

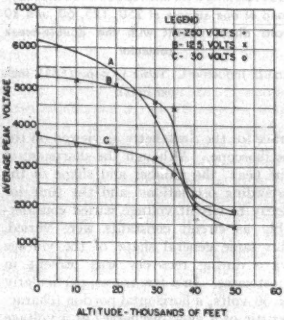

Figure 12. Average peak voltage (ten readings) versus altitude resulting from interruption of an inductive load of 0.4 ampere at 250, 125, and 30 volts direct current with the double-break Switchette

Load: inductive *A*, Table I; gap: 0.020 inch per break

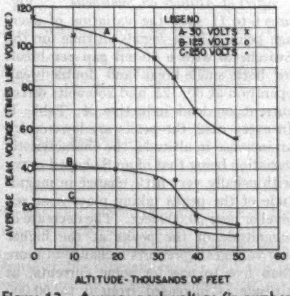

Figure 13. Average peak voltage (in number of times normal line voltage) versus altitude resulting from interruption of an inductive load of 0.4 ampere at 250, 125, and 30 volts direct current with the double-break Switchette

Load: inductive *A*, Table I; gap: 0.020 inch per break

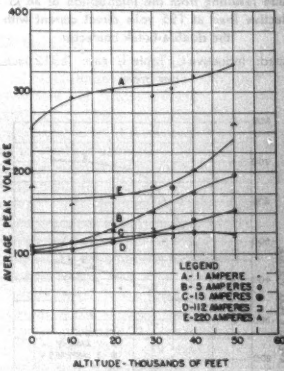

Figure 15. Average peak voltage versus altitude resulting from the interruption of an inductive load at 30 volts direct current with the double-break contactor

Load: inductive *C*, Table I; gap: 0.312 inch per break

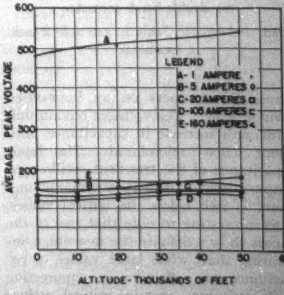

Figure 16. Average peak voltage versus altitude resulting from the interruption of an inductive load at 60 volts direct current with the double-break contactor

Load: inductive *C*, Table I; gap: 0.312 inch per break

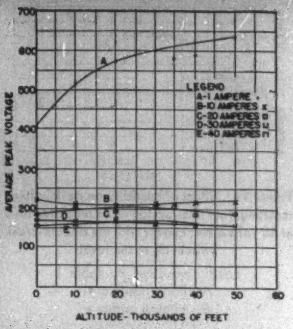

Figure 17. Average peak voltage versus altitude resulting from the interruption of an inductive load at 125 volts direct current with the double-break contactor

Load: inductive C, Table I; gap: 0.312 inch per break

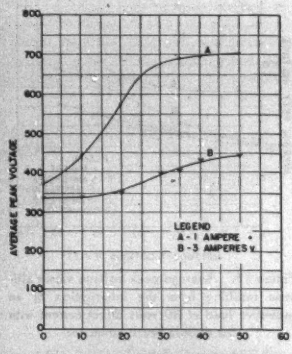

Figure 18. Average peak voltage versus altitude resulting from the interruption of an inductive load at 250 volts direct current with the double-break contactor

Load: inductive C, Table I; gap 0.312 inch per break

across the contacts on an improvised semilog scale. The voltages remain uniform with increase in capacitance until about 0.0001 microfarad. The input capacitance of the transient oscilloscope is approximately 0.00003 microfarad, and hence is well below the critical values. It is interesting to note that two of the curves show a definite rise in voltage, indicating that, while large values of capacitance are effective in suppressing peak voltages, certain critical values may give rise to abnormally high peaks.

Test Results

Wave Shape of Typical Interruptions. In Figure 5 is shown a typical recovery

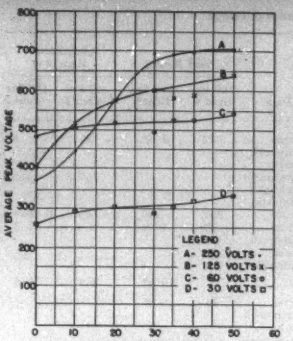

Figure 19. Average peak voltage versus altitude resulting from interruption of an inductive load of one ampere at 250, 125, 60, and 30 volts direct current with the double-break contactor

Load: inductive C, Table I; gap: 0.312 inch per break

trace for the Switchette as viewed on the oscilloscope. Although the sharpness of the peak, the number and shape of the preceding oscillations, and the time for decay to circuit voltage varied considerably as circuit constants were varied, this same general shape of the voltage wave during recovery was present in most cases. In a few traces, particularly at 30 volts, a horizontal portion (characteristic of a glow discharge) at a voltage several times line voltage appeared sometimes before and sometimes after the peak. In general the peaks occurring with the double-break contactor appeared much sharper than those with the Switchette, and build-up and decay periods were longer and had less oscillatory disturbance.

Effect of Altitude on Switchette. Figures 6 to 11 show the variation of average peak voltage versus altitude for the Switchette with a 20-mil gap per break for both single-break and double-break operation at 30, 125, and 250 volts direct current on load inductive *A*, Table I. In every case, the peaks are lowered by an increase in altitude, the characteristic variation being that of an S-shaped curve with usually very little change in magnitude of the peaks taking place near sea level or near 50,000 feet. The decrease in magnitude of the peaks at the higher line voltages represents a change of more than five to one for some currents, as altitude is increased from 0 to 50,000 feet.

Effect of Current on Switchette. It should be noted that in most cases as current is increased from a very low value up to 0.4 or 0.6 ampere, the magnitude of the peak increases, after which an increase in current lowers the peaks.

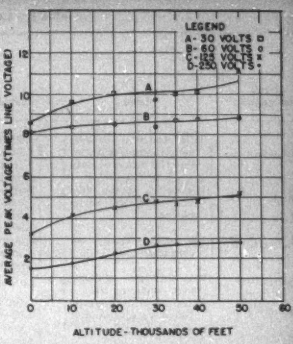

Figure 20. Average peak voltage (in number of times normal line voltage) versus altitude resulting from interruption of an inductive load of one ampere at 250, 125, 60, and 30 volts direct current with the double-break contactor

Load: inductive C, Table I; gap: 0.312 inch per break

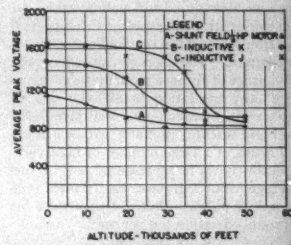

Figure 21. Average peak voltage versus altitude resulting from interruption of inductive loads at 30 volts direct current with the double-break Switchette

Load: aircraft devices now found on 30-volt systems. See Table I

There is some reason, based on tests not reported here, to believe that the magnitude of the peaks again increases as the current approaches some considerably higher value, providing of course that the interrupting limit is not exceeded. This variation of the peaks with current is much more noticeable at sea level than at high altitude.

Effect of Line Voltage on Switchette. In order to show the comparative peak voltages attained with the three different applied voltages at the same current, Figure 12 is plotted. This indicates the comparative severity of the peaks under one of the worst conditions—that is, 0.4 ampere, double-break. The same effect is shown perhaps more spectacularly by Figure 13 in which the ordinates have been changed from absolute voltage to number of times line voltage. In mak-

ing this comparison at different line voltages, it should be noticed that the inductance values are different. The inductances at 30 and 125 volts are about the same, whereas that at 250 volts is considerably lower.

Effect of Humidity. In order to show the effect of humidity on peak voltages, a run was taken at 30 volts, zero altitude and the results plotted in Figure 14, showing peak voltages as a function of current, both at room humidity and a very high relative humidity (near 100 per cent). According to these results, a wide variation in humidity does not affect materially the magnitude of the peaks.

Effect of Altitude on Double-Break Contactor. To cover higher-current ranges, Figures 15 to 18 are presented for the double-break contactor. It will be seen that the general tendency is for peak voltages to stay fairly constant or to increase somewhat with altitude, depending upon the current interrupted. Noteworthy here are the curves for the 60-volt and 125-volt supplies where the peaks at one ampere jump to two or three times those at the higher currents. In general, in the current range used here the peaks decrease with increasing current, though this decrease is small at the higher currents. There is, however, some indication again of an increase in the peaks at some fairly high current (Figures 15 and 16).

The peak voltages versus altitude resulting from the interruption of one ampere at the four voltages are shown on Figures 19 and 20.

Typical Aircraft Loads. Figure 21 shows the peaks resulting from interruption of a 30-volt circuit by the Switchette (double-break) using inductive loads *J* and *K* and the shunt field of a one-ninth-horsepower motor, all of which are typical aircraft devices. In the first two cases, the current was something above one-half ampere; and in the latter case, about one-quarter ampere. It must be realized, however, that the inductances dealt with here were much smaller, than those of load inductive *A*. Inductive load *H* was also tested and gave very nearly the same peaks as *K*. These peaks must not be construed to be the maximum occurring with any aircraft device, but were taken as being for typical applications. Other devices, possibly with critical values of lead capacitance, might give rise to higher values than for the cases shown.

Conclusions

Experimental data presented in this paper show that voltages of 7,000 volts are possible across the contacts of a switch-interrupting direct current. While the breakdown effect of these peak voltages has not been studied, it is quite possible that they are sufficiently high to cause insulation breakdown or tracking. It was also shown that these peaks are not always worse at altitude.

The two devices investigated gave considerably different results, but this is not surprising, for the devices were not similar. Furthermore, the load ranges and values of inductance differed widely. The subject requires a considerable amount of further investigation.

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Very High-Frequency Radio-Noise Elimination

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THE subject of radio-noise elimination on aircraft has always been a controversial one, even when the frequencies involved were relatively low. With the introduction of very high-frequency equipment the controversy has started afresh. The presence of radio noise in very high-frequency installations has caused observers to forget the principles learned in the work at medium frequency and high frequency, simply because the very high-frequency installation apparently did not follow the same rules that applied to the lower-frequency equipment. It is the purpose of this paper to outline generally the principles of radio-noise elimination at all frequencies, and show how these same principles apply specifically at very high frequency.

Because of the variety of conditions which may be encountered in aircraft radio-noise tests, it will not be possible to detail the test procedures and corrective measures necessary for very high-frequency radio-noise elimination. Rather, it is desired to discuss basic concepts in such a manner that radio-noise test procedure can be made a matter of routine. An outline of test procedure insofar as the engine ignition system is concerned is given, and the remedial measures necessary are generally indicated. The whole procedure is based upon the concept of determining the coupling path into the receiver, with the idea in mind that once this is known the method of eliminating the coupling path is best reached by a consideration of the construction of the airplane under test.

It is unfortunate that many of the terms in use in radio-noise-elimination work are so broad and ill-defined that they cannot be used without careful definition. Since the loose use of these terms has led to some confusion, immediately following a list of definitions is given.

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Definitions

A *radio-influence source* is defined as a generator of radio-influence voltages, currents, or fields, and which is capable of exciting a radio receiver in such a way as to produce acoustic output, providing the necessary coupling exists between the radio-influence source and the radio receiver. This implies that the radio-influence source is only influential in providing such an output, and that the measurement of the source is not a measure of the final result.

Radio noise refers specifically to that portion of the acoustic output of a radio receiver produced by coupling a radio-influence source in any manner whatsoever to the radio receiver.

A *coupling source* or *path* is defined as the impedance or circuit element which is excited by the radio-influence source so as to produce acoustic noise in the output of the radio receiver. The coupling source or path may be the radio-influence source in some cases, but may be any part of a circuit, such as a wire, in which radio-influence currents are flowing.

Ground plane—structure ground. Although separated from earth, the metal body of the aircraft acts as a reference plane for the purpose of this paper, and all potentials are in reference to this point. The plane of ground potential is not an obscure hypothetical plane diffi-

cult to locate as in many earth transmission problems, but is a sharply defined plane of nearly uniform potential existing directly at any metal portion of the structure.

Antenna refers only to the portion of the antenna circuit outside the fuselage, and specifically excepts any portion which is inside the fuselage.

Leadin refers only to the portion of the antenna circuit which is either inside the fuselage or is shielded in any way to prevent undesired coupling of any type.

The *antenna circuit* of a radio receiver is defined as that circuit through which the current flows as a result of signal voltages generated in the antenna due to its presence in a radiation field from a transmitter antenna. As such, it includes the antenna, the leadin (either shielded or unshielded), the receiver input circuit, and the ground-return circuit.

Methods of Radio-Noise Generation

The radio-influence generators with which we are most concerned are those within the airplane itself, and are almost exclusively electrical devices of one sort or another. At medium frequency and high frequency almost any electrical device may act as a generator of radio influence, but at very high frequency the main source is the engine ignition system. Other devices may be troublesome, but these cases are infrequent. They will be dealt with later in this paper.

The Aircraft Ignition System

The aircraft ignition system consists essentially of a high-voltage magneto and distributor. See Figure 1 for a sketch of the system.

In the magneto itself, the primary circuit is controlled by the opening and closing of a contact switch. The secondary circuit is connected through the distributor to the appropriate spark plug. Provisions are made for starting by the use of either a booster coil or an ignition vibrator; the booster coil feeds high voltage directly into the distributor, while the ignition-vibrator type is directly connected to the magneto primary coil. In either case, operating power is supplied by the d-c power system of the airplane.

In order that the pilot may control the ignition system, a wire from the primary side of the magneto is run to a control switch in the cockpit. Here, provisions are made for grounding the primary of the magneto. The very steep fronts characterizing the voltage in the primary circuit (see Figure 1A) make it capable of impulse exciting any circuit to which it is coupled. For this reason the magneto grounding switch and the grounding leads should be well shielded. The switch should be one in which the battery switch is not included, and should be grounded to basic structure as close to the switch as possible. If the grounding wire runs outside the ignition switch box, it should be shielded also.

Since the voltage in the secondary circuit is definitely of oscillatory character (see Figure 1B), it is necessary to shield every portion of this circuit very thoroughly. The instantaneous energy content of these oscillations is very high, and the frequency range goes up into the superhigh-frequency region.

The oscillatory circuit, composed in the main of the spark plug, the spark-plug-lead capacitance and inductance, is not a simple circuit. There may be several oscillatory circuits set up, each with its own fundamental frequency. The lowest-frequency circuit will be that one utilizing the full-lead inductance and capacitance; peak currents here may go as high as 85 amperes.[1] A higher-frequency oscillatory circuit may be one formed by the spark plug itself, and peak currents here may run from 100 to 175 amperes.[2] Furthermore, there may be a local oscillatory circuit formed in the magneto and distributor housing, with peak currents here also running into high magnitudes.

It must be appreciated that the shielding of circuits containing currents of such high magnitudes is not an easy matter. The design of all mating parts must be such as to reduce the impedance to as low a value as possible; simple butt joints, pressure-held, are unsatisfactory, as they rarely permit continuous contact surface. In a conduit coupling joint, for example, it is not enough that contact be made at one or two points on the circumference of the fitting. There must be a number of contacts about the circumference, so that the radio-frequency current may have a flow path at any point, and the current density about the joint is evenly distributed.

Since the booster coil is connected directly into the distributor, and is operated by the airplane's electric system, it provides a simple method whereby the radio-frequency energy generated in the high-voltage system may be coupled into the aircraft wiring system. The ignition vibrator, on the other hand, connects to the low-voltage side. This is also a coupling path to the aircraft wiring system, but is not so effective as the one through the booster coil. In either case it is wise to place a high-frequency filter in the positive feed to these devices.

Up to now the magneto grounding leads have been treated as if they carried only the pulses which are characteristic of the low-voltage side of the ignition system. However, since these leads enter the magneto, it is inevitable that they should be affected to some extent by the radio-frequency fields set up by the secondary or high-voltage system. They do carry small radio-frequency currents from this source, but generally the amplitude of these currents is small and not nearly so effective in causing radio noise as the pulses set up by the action of the contacts.

The aircraft ignition system, therefore, may be divided into two parts as far as its radio-influence generating capacities are concerned. First, there is the low voltage or primary side of the magneto; the only coupling path for this system is through the magneto grounding leads and the ignition vibrator. Second, there is the high-voltage side or secondary side, which may radiate directly, or may couple through the booster coil. These coupling paths are the only ones by which the engine ignition system may transfer radio-frequency energy outside itself. This last statement must be considered carefully by those making radio-noise investigations. If all these coupling paths are controlled, there is no chance of radio-noise troubles. Radio-noise investigations involving the ignition system are simply problems of determining the coupling path and eliminating it. The high-voltage system may be the most difficult to control, as such high peak energies are involved, and the return paths for the radio-frequency currents are often difficult to control. Magneto and distributor construction is such as to provide possible high resistances in the current return path, such as the mating surfaces between magneto and distributor parts. However, the currents here are low in value compared with those in the spark-plug leads (except where local oscillatory circuits are formed), and are controlled much more easily. This is almost entirely a matter of good magneto and distributor design.

Other Radio-Noise Sources

As previously noted, other radio-noise sources are very few in number, particularly at very high frequency. What few there are depend upon their ability to produce a voltage surge with a steep wave-front, so almost any interrupting device may be effective. Cases have been encountered where small motors have caused trouble, even though no commutator trouble was evident. Here the motor was high speed, with consequent high-frequency commutator ripple, and was mounted upon a plywood deck where bonding was difficult. Good bonding was the answer in all cases.

Ignition systems for heaters have been developed in the past few years which are a modification of the aircraft-engine ignition system. That is, either a spark coil controlled by an interrupter and fed from the d-c power system may supply a conventional spark plug, or a transformer operating off the 400-cycle supply may operate the spark plug. In either case, a great deal of interference may result. The problems presented by this system are identical to those presented by the engine ignition system, with the added complication that the equipment is lo-

cated within the fuselage. It is necessary to shield the secondary circuit very thoroughly, whereas the primary circuit must be well filtered.

As is well known, radio-influence sources are plentiful at medium frequency and high frequency, and are usually motors of one sort or another; dynamotors are apt to be particularly troublesome. In any event, none of the devices will cause trouble if the coupling paths once are determined and eliminated. A small amount of induction coupling is evident from some of these devices on occasion, particularly if they are unbonded. If the leadins are run clear of the motors no trouble will be experienced in any but the exceptional case. The main coupling path is through the aircraft wiring, and this will be dealt with later.

The aforementioned references to bonding must not be construed to mean that bonding connectors are to be used; it is only necessary that the motor or dynamotor case be well grounded through the usual bolts or clips. Where the part is mounted upon a wooden deck it is usual to provide good bonding to the nearest structure.

Methods of Radio-Noise Transmission

The output of a radio-influence generator is of no consequence if a coupling path does not exist between the generator and some impedance element in the receiver input circuit. For some time it was believed that either the antenna or the antenna leadin was always the impedance element affected and that radiation was the coupling path, but this has been disproved largely at medium and high frequency. At these frequencies, the antenna is almost never affected by radio-influence sources within the airplane. The coupling path is almost invariably the aircraft wiring system, either by coupling to the leadin or common impedance coupling which will be discussed later.

At very high frequency the situation is somewhat different; direct coupling may occur to the engine ignition system, and the antenna will be the impedance element affected. There are, however, other coupling paths at these frequencies, and it is the purpose of this section to discuss these paths.

Before proceeding with the discussion it must be pointed out that the conventional methods of measuring radio-influence sources are in error, in that only the voltage is measured. The voltage measured is a function of the internal impedance of the source, the impedance of the external circuit to which it is connected, and the open-circuit voltage of the source, and consequently will change rapidly with any change in the output-circuit impedance. Resonance effects also enter, as the aircraft wiring system must be considered as an impedance network. It is therefore possible to have high voltage and low current at the radio-influence source output, and low voltage and high current at some point in the network, and vice versa. In any event, since either electromagnetic, electrostatic, radiation, or any combination of these couplings may occur, and both the current and the voltage at the impedance element through which coupling occurs must be taken into account, voltage measurements alone are insufficient.

The Aircraft Wiring System—Unshielded

As might be expected, the aircraft wiring system exhibits transmission-line characteristics. To determine the attenuation that might be encountered in a section of aircraft wiring, a series of tests was made on a typical aircraft open wiring bundle consisting of 15 wires. The results of this test are shown in Figure 2, where the attenuation of the aircraft wiring is compared with the attenuation of conventional coaxial cables. For the aircraft wiring the measurements were made between one wire and structure ground. It will be noted that, while the attenuation of aircraft wiring is considerably higher than for a good twin-conductor coaxial cable, it was only slightly higher than for a rubber-insulated twisted pair. The curves shown would be entirely valid if aircraft wiring consisted of simple runs from one point to another, but it does not. The aircraft wiring bundle may contain a number of cables, terminating in lights, switches, or other devices, and an analysis of the aircraft wiring system on the basis of a transmission line would not be very useful. It is preferable to consider it on the basis of an impedance network, as previously noted. On that basis the voltage and current relationships in any network element are a function of the impedance, the voltage and current, and the mutual inductance relationships of all the other elements, plus the generator voltage and internal impedance. Even an approximate calculation of the relationships would be very complex, this consideration being presented simply to indicate the type of approach necessary. An approach by means of voltage measurements alone is inherently faulty.

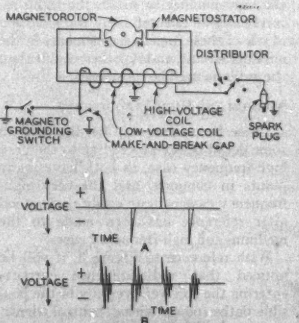

Figure 1. Aircraft ignition system

Magnetorotor, distributor, and make-and-break gap. All are engine-driven and set to produce spark at proper moment in engine cycle

A. Voltage on magneto grounding wire, peak about 200 volts

B. Voltage in secondary circuit, peak depending on pressure, gap spacing, and so forth—about 15,000 volts

It is evident that aircraft open wiring of itself cannot be depended upon for any large attenuation, except in rather long runs. It is also evident that aircraft open wiring will act precisely like any other transmission line used to couple a generator to a terminal impedance. If there is a mismatch, reflections will occur with the formation of standing waves upon the line. Since one or more wires in a bundle may be carrying a wave from the same radio-influence source, but fed over a slightly different path, the standing waves on one wire will not agree in location with the standing waves on other wires. The result of this will be that any attempt to locate standing waves with a noisemeter will be quite confusing, especially at the higher frequencies.

It is probable that this has contributed to the many attempts at source suppression; the whole fuselage area seems full of "noise" and source filtering does eliminate it. The factors which make source filtering impractical have been reviewed in other literature, however, and will not be taken up here.[3]

The Aircraft Wiring System—Shielded

A discussion of the portion of the aircraft wiring that is still shielded may seem academic, as there is so little of it left. Nevertheless, the portions that remain shielded are quite important and deserve attention. In the main, these portions are the ignition system, particularly the magneto grounding leads.

The shielded wiring also may be considered as a transmission line. The attenuation here is somewhat greater than for open wiring, since a great portion of the area of the conduit is filled with a dielectric of relatively high loss at high frequencies. Current flows on the conductors inside the conduit and upon the inner surface of the conduit exactly as in a coaxial cable, the resultant field being confined within the conduit for all practical purposes.

A conduit, either solid or flexible, may contain a joint at some place in the line, and such joints easily may be of rather high resistance, if the joint is not well made. If this local area of high imped-

ance is located where the current density is high, the current will seek a better path, in many instances flowing entirely outside the conduit. This area of high current density outside the conduit will create a local field and may excite conduit which is some appropriate multiple of one-quarter wave. If this field is set up in a section that is not well shielded or near one of the openings in the fuselage, radiation may take place outside the fuselage, and the antenna will be affected directly.

It must be emphasized here that the field produced by current flow outside the conduit is not the same field that is found within the conduit and which is created by interaction between the current flowing on the conductors and on the inner surface of the conduit. That is, it must not be conceived that the field within the conduit penetrates through the conduit in some manner; nothing of the sort occurs. A better conception is that the field within the conduit is the power-transmission medium, and the currents that flow are set up by the field and are a source of losses. When these currents flow outside the conduit a local field is created there, incidentally introducing another loss.

Radiation is most likely to take place from the engine-section ignition system, which in most cases is enclosed in flexible conduit. The leads to the spark plugs are very high-frequency oscillatory circuits, as previously noted, and the current density at joints or glands may be extremely high. A poor joint in this area cannot be tolerated; the field set up about the joint is of such intensity that the engine cowling is insufficient to attenuate it, and direct coupling to the antenna results.

Flexible conduit is often suspected of radiation, since it is almost invariably possible to detect a small field about it. This is the result of the in-and-out weave of the outer sheath, a small portion of the current flowing upon the inner surface of the conduit being conducted to the outside surface, setting up a small field there. The field noticed is the resultant of all the fields set up by the tiny currents flowing outside the conduit.

The field about flexible conduit is commonly known as a "leak," the inference being that radio waves or even the field between the inner and outer conductors actually leaks out between the wires composing the weave. The term "leak" is unfortunate, as it does not describe adequately what is taking place. The same term, also used incorrectly, is applied to describe the fields set up by current flows at the mating surfaces between the magneto and the distributor, or between the magneto and the engine. A slight consideration will show that the spaces where such "leaks" are believed to take place are so much smaller than the length of the wave

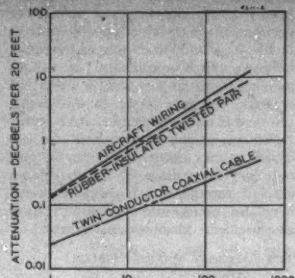

Figure 2. Attenuation of various types of transmission lines

in question that actual leakage cannot take place. The remedy ordinarily prescribed to cure this "leak," that of grinding the mating surfaces so that contact will be uniform, simply provides a low-impedance path for the current, so that it is not forced to seek a path which lies outside the magneto.

Common Impedance Coupling

Mention has been made previously as to the introduction of radio noise into a receiver by the formation of a radio-influence voltage across the impedance between the receiver chassis and ground, the impedance being directly in the antenna circuit of the receiver. Such cases are more common than is realized, and are more responsible for radio noise than is ordinarily believed. Inasmuch as any such voltage will of necessity be small, the only manner in which the radio receiver can be affected is by the inclusion of one of these impedance elements in the antenna circuit, and no other circuit than the antenna need be considered.

Medium and High Frequencies

These frequencies will be discussed in some detail before proceeding to the very high-frequency case, as both have many points in common, and the very high-frequency case is more easily understood after reference has been made to the medium- and high-frequency cases.

With reference to Figure 3, it will be noticed that radio-influence currents entering the receiver over any of the possible paths (power wiring, control wiring, and so forth) must flow to structure through the ground impedance, which is composed of the bonding connector, and any other impedance path present, all being in parallel. This impedance is of a very complex nature and may be either capacitative or inductive, depending upon the installation and the frequency. This is because the impedance of a bonding connector goes up rapidly with frequency, while the reactance offered by the capacitance between the chassis and structure decreases with frequency. In any event, a complex voltage is formed across the impedance, and an inspection of the block diagram will show that this voltage is directly in series with the antenna circuit. For all intents and purposes, then, there are two generators in the antenna circuit. First, the equivalent signal generator, which has an internal impedance equal to the antenna impedance and an output voltage equal to the signal induced in the antenna by the electromagnetic waves from the station being received. Second, the equivalent radio-influence source, which has an internal impedance equal to the ground impedance and a voltage equal to the product of the radio-influence current through it and the ground impedance. This is shown in Figure 3. The voltage which appears across the input circuit of the receiver is the resultant of the vector addition of the signal and radio-influence currents times the impedance of the input circuit. Since signal voltages are apt to be low, it will not require much current flowing through the bonding impedance to provide a voltage at least equal to the signal voltage and probably much larger.

It is apparent that the installation of coaxial cable or twisted pairs in the leadin on many installations other than on aircraft are effective in controlling "noise," not because induced "noise" voltages are balanced out, but because common impedance coupling is eliminated. It may be very difficult to make a separation test that will differentiate between coupling to the leadin and common impedance coupling, except in an all-metal airplane where the leadin is adequately shielded.

Three conditions must be observed in any separation test to determine the effect of common ground-impedance coupling. These are:

1. Exclude from the antenna circuit that portion which is exposed to direct coupling; that is, the antenna itself.

2. Retain within the antenna circuit all current-flow paths that are present in the normal circuit; that is, the ground connections at the receiver and the antenna mast should remain intact.

3. Replace the antenna with an equivalent impedance. At medium frequency and high frequency this may consist of a capacitor approximately equivalent to the capacitance of the antenna to the fuselage; at very high frequency the impedance should approximate that of the antenna at the frequencies being considered.

All conditions must be observed, or else the separation test will be invalid. The first condition is more or less obvious, but not the second and third. However, it must be remembered that, if the antenna-circuit-impedance relations are changed, the various portions of the test cannot be correlated, and the test results will be meaningless.

Very High Frequency and Ultrahigh Frequency

Very high-frequency and ultrahigh-frequency receivers are invariably coupled to the antenna by some form of coaxial cable, with the outer sheath ordinarily of a flexible weave to facilitate installation and maintenance. At the receiver and at the antenna this cable terminates in a special fitting, so that it may be disconnected readily, again to facilitate installation and maintenance. Each of these breaks in the coaxial cable run introduces an additional impedance, however slight. The greatest source of extraneous impedance elements are these fittings, especially where the antenna circuits have not been designed with the elimination of radio noise in mind. A typical example, using a current very high-frequency transmitter–receiver, will be given.

The coaxial fitting is on top of the transmitter–receiver (an error to begin with, as any currents induced in the coaxial cable sheath have a relatively long path to travel to ground and can get into all sorts of mischief along the way); the center conductor is brought down to the antenna switching relay, where, by means of long leaf-type spring contacts, connection is made either to the receiver or transmitter. The connection to the receiver input coil is well routed, but the input coil is grounded directly to the chassis, forcing the antenna signal currents to travel back to the coaxial fitting over the best path possible. The coaxial cable fitting is grounded to the chassis by means of the mounting bolts and a copper lead, but is held about an inch off the main chassis by the mounting bolts, so that the sheet-metal-case cover is flush with the base of the coaxial fitting.

Several impedance elements are apparent here: the impedance of the fitting itself, the impedance between the fitting and the chassis, and the impedance between the ground point of the coaxial fitting and the receiver input coil. Obviously, the total impedance between the end of the coaxial cable and the ground point of the receiver input coil will raise the fitting above ground potential, as far as the receiver is concerned. It has been observed that, with the antenna terminal shielded, touching or even bringing the finger close to the coaxial fitting will bring the receiver up to full output level, if even a weak field is present.

On this same transmitter–receiver the coaxial cable fitting to the antenna mast introduces another long lead from the fitting to the ground stud on the mast. Ordinarily not too much attention is paid to the ground connection between this stud and structure, so this may also be of high impedance, particularly if ordinary bonding braid is used. The bonding connector here should be as short as possible and preferably of copper strap.

Ordinary flexible shielding, such as is used on shielded leads on interphone systems, has been shown to have an attenuation of 60 decibels, and it is very unlikely that fields are present inside the airplane fuselage of sufficient strength to induce voltages in the inner conductor of a coaxial cable. There are, however, fields due to standing waves present upon the aircraft wiring, and wherever wiring and coaxial cables run in parallel, it is a very simple matter to set up a current flowing along the outer surface of the sheath.

The interference that may result from current flow in coaxial cable sheaths has been investigated thoroughly. A test setup of the receiver previously mentioned was made substantially as follows: all control and power wiring to the receiver was isolated and shielded by copper sheeting, all joints being well soldered, and all possible coupling to the receiver from this path eliminated. A coaxial cable with solid dielectric insulation, standard sheath weave and vinyl covering was extended about 15 feet away, the free end suitably terminated in the characteristic impedance of the cable with the terminal impedance also shielded. A very high-frequency signal generator was set up with an insulated coupling lead two feet long taped to the coaxial cable. With a fixed output of the signal generator the receiver output level was noted before and after the coaxial cable fitting was bonded to the chassis.

The results of this test in terms of decibels rise above the background level (reference level, one milliwatt in a 600-ohm line) were 24-decibel rise with the coaxial fitting unbonded; two-decibel rise when bonded.

It thus was concluded that common impedance coupling was responsible for the increases in output level. To test the accuracy of this conclusion, the antenna connector of the receiver was terminated at the coaxial fitting and shielded so that no coupling could occur; then the sheath of the coaxial cable was attached to the fitting. Coupling to the coaxial cable was accomplished as before, and it was found that, with approximately the same signal level from the signal generator as before, the output level of the receiver was 27 decibels above the background level. The installation of a bond on the coaxial fitting caused a decrease in output level of 21 decibels.

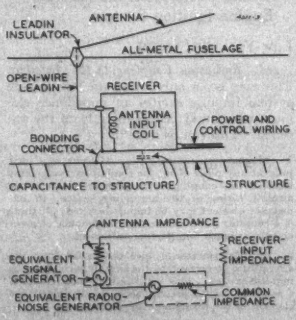

Figure 3. Common impedance coupling

A. Block diagram of typical radio-receiver installation at medium and high frequency

B. Equivalent circuit diagram usable for any frequency range

To summarize, it is evident that a receiver, although fitted with a coaxial cable, may be affected by currents in the coaxial cable sheath. This is accomplished by the currents flowing through a relatively high impedance common to the antenna circuit of the receiver. Such an impedance may be one formed at any portion of the antenna circuit by a discontinuity, or in any portion of the circuit in which both the antenna current and the radio-influence currents flow over the same path.

Elimination of Very High-Frequency Radio Noise

The proper starting point in the elimination of radio noise at any frequency is in the design of the radio receiver. Unfortunately, the designer usually is concerned mostly with circuit design, the antenna being only the means of introducing a signal of certain characteristics, so that something else happens at the output end of the receiver. Bench testing is done under conditions which do not approximate those in service with the result that a receiver which performs perfectly under test may be noisy when installed in the airplane. Then in an effort to eliminate the interference various methods of interference suppression are used, including filters upon all items of suspected electric equipment, bonding, and shielding.

Interference suppression by the means enumerated has become a sort of obsession, so much so that suppression methods are applied by specification requirements to all equipment, whether or not they produce radio noise. In view of the demonstrated fact that much of this interference could be eliminated by proper design of the radio receiver, it is at once apparent that the suppression devices added are largely dead weight, decreasing the pay or bomb load, as the case may be.

Lest the whole burden of the blame be shifted too quickly to the radio-equipment designer, it should be said here that the blame rests equally upon him, the designer of the electrical equipment producing the interference, and the designer of the radio installation in the airplane. A very great deal can be done by the equipment designer, for, while we know of no way as yet to correlate the radio-influence voltage of a device with the radio noise this device produces in

the receiver, we do know that a motor can be designed to create a minimum of radio-influence voltage. The electrical-equipment designer must have not only the performance of his design in mind; he must consider its effect upon other equipment. The extra weight in filters, and so forth, which is necessary to make one item of equipment comparable in all respects to another item is directly chargeable to that item.

The designer of a radio installation may destroy entirely the good work of the radio-equipment designer and the electrical-equipment designer. Long antenna leadins are sometimes unavoidable, but it is inexcusable to place wiring or rotating equipment in close proximity to that leadin without taking adequate precautions so that there will be no interference. But inasmuch as the radio-installation designer is confronted with the problem of making presently available equipment function properly, it is necessary that this designer know the methods which are practical and workable for the reduction and elimination of radio noise.

To this end, in the section to follow, the general outlines of a test program are given, specifically for very high-frequency radio-noise tests. Before any such test is made the test man must make himself thoroughly familiar with the airplane upon which he is working insofar as the electric and ignition system are concerned. All ignition-system wiring should be traced out, both on the wiring diagram and on the airplane itself. The installation of the radio equipment should receive the most careful consideration, the feed points of the power supply, the location of the control equipment and wiring to it, and the run of the coaxial cable from the antenna to the receiver; all should be well fixed in mind. After this, the test man should determine the points at which the separation tests are to be made. Finally, he should set down in a logical sequence the tests he intends to make, and this sequence should be followed at all costs during the tests. This latter is especially important, as it is very easy to allow oneself to be distracted during the tests. The result is that invariably the most important test is left out, and a guess will have to be made at the results that should be on hand.

Test equipment need not be elaborate. There should be prepared beforehand a list of needed equipment, which of course will be dictated to some extent by the available equipment and the experience of the test man. A complete listing will not be given here, but three items must be considered:

1. *Antenna termination.* This should be a shielded box, containing an impedance approximately equal to that of the antenna it is to replace with a fitting, so that the coaxial cable can be attached, and another fitting, so that the box may be attached to where the coaxial cable normally goes. This is important, as it preserves the continuity of the ground circuit of the coaxial cable sheath.

2. *Shielded oscillator.* This oscillator should be fitted so that it can be attached to the magneto pencils or one of the spark plugs. In this way, tests can be made upon the effect of the magneto grounding wires, or loose coupling and gland nuts may be found while the engine is not running.

3. *Duplicate receiver.* The radio receiver as mounted in the airplane may be surrounded by intense fields created by wiring carrying radio-influence currents, and probe tests made with this receiver may be misleading. It is desirable to have a duplicate receiver for such tests, complete with power supply. If the receiver and power supply are mounted on a metal panel and placed on a dolly, they may be moved as convenience dictates and will prove very useful.

No attempts should be made to interpret the results of the probe test in terms of absolute field strength; this is virtually impossible. Any comparisons made should be on the basis of a qualitative analysis only. Field-strength measurement at any frequency is a laboratory test; this is especially true at very high frequency.

Very High-Frequency Radio-Noise Test Analysis

Inasmuch as the main radio-influence source at very high frequency is the engine ignition system, this source alone will be considered here. As the preceding text has indicated, the ignition system may be broken down conveniently into two parts: the high-voltage and low-voltage sides. These will be taken up separately, and the various coupling paths will be considered.

Coupling Paths from the Aircraft-Engine Ignition System

Low-Voltage System

(*a*). *Radiation Coupling to the Antenna.* This may occur only where the low-voltage system impulse excites an impedance element which may couple directly to the antenna. This can be done by:

1. Magneto grounding leads. If there is a poor joint at any place along the conduit carrying these leads, or any coupling between these leads and the aircraft wiring at the grounding switch, an impedance element may be impulse-excited. If there is a coupling path between this impedance element and the antenna, interference will result.

2. Ignition vibrator. Since this is fed from the aircraft d-c power system, the aircraft wiring may be impulse-excited. This will result in interference if a coupling path is present between any impedance element of the wiring and the antenna.

(*b*). *Conduction Coupling.* This occurs where currents are induced by any means whatsoever in any portion of the antenna system other than the antenna itself. It may be caused by the magneto grounding leads or the ignition-vibrator feed wire impulse-exciting any portion of the aircraft wiring system.

High-Voltage System

(*a*). *Radiation Coupling to the Antenna.*

1. Direct coupling. This may occur where any portion of the high-voltage ignition system is in such condition as to set up a local field which couples directly to the antenna.

2. Coupling through some other impedance element. Radio-frequency currents fed through any path, either the magneto grounding leads or the booster coil leads, may excite some impedance element from which there is a coupling path to the antenna.

(*b*). *Conduction Coupling.* This is analogous to conduction coupling in the low-voltage system and occurs where radio-frequency energy is coupled into the aircraft wiring system from the magneto grounding leads or the booster coil, inducing a current into some impedance element of the antenna circuit.

The breakdown given may seem oversimplified, but it is all there. It is important to realize that there are only a few coupling paths from the aircraft-engine ignition system, and then plan the test procedure to isolate them one at a time.

As a basic test procedure, the following is suggested: Pull the magneto grounding pencils and then disconnect the leads to the booster or ignition vibrator. If radio noise still persists, stop the engines and feed a signal from the oscillator into one of the spark-plug leads. A probe test will show which coupling is loose; often it is necessary only to short-circuit across the suspected connections with a screw driver to check the effectiveness of the electrical path through them.

Next, with the ignition harness cleaned up, run the engines with the booster or ignition coil connected and the magneto grounding pencils disconnected, then vice versa.

This procedure definitely will indicate the coupling paths; it then will devolve upon the test man to determine the circuit elements through which coupling is occurring.

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Altitude Rating of Electric Apparatus

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THE proper functioning of electric equipment is of prime importance in the operation of the military and naval airplane of today. The wide use of such equipment and the continual increase in the operating altitude of aircraft make it essential that the factors affecting the operation of electric apparatus at high altitudes be investigated if the apparatus is to be designed properly for this new and expanding application.

This paper studies the effect of altitude on the ratings of rotating electric machines and, after determining the fundamental principles involved, discusses these in relation to the application of such machines in modern aircraft. It is shown that the rating of a self-ventilated direct engine-driven aircraft generator decreases rapidly with altitude and, at some altitude within the operating range of the airplane, the generator may be able to dissipate only its no-load losses. It is shown also that an air-scoop-ventilated direct engine-driven aircraft generator maintains its rating over most of the operating range of present-day aircraft. Finally, certain sea-level tests are proposed from which calculations of rating under altitude conditions can be made.

The theory and tests presented in this paper have been checked by altitude-chamber studies on an aircraft-type d-c generator.

Fundamental Analysis

Heat Transfer in Electric Machines

One of the principal factors determining the rating of electric apparatus is the maximum temperature to which its insulation can be subjected without failure during the required life of the machine. This operating temperature is a function of the losses of the machine and its ability to dissipate the resultant heat.

An electric machine may dissipate its losses by four means:

1. Forced convection between winding and core surfaces and cooling air.
2. Free convection between frame and ambient air.
3. Radiation between frame and surrounding objects.
4. Conduction between frame and mounting.

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The watts loss which may be dissipated by these processes is a function of the temperature difference between the machine surfaces and the ambient temperatures. The machine temperature rises until the total watts loss dissipated just equals the input losses; that is, until equilibrium is reached. Thus, any increase in load (and hence, loss) will increase the machine temperature unless the additional heat can be removed from the machine by an increased heat transfer. Conversely, any reduction in heat transfer will increase the machine temperature unless the loss is reduced.

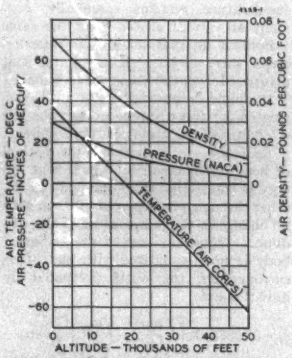


Figure 1. Properties of atmospheric air

The heat transfer between the machine and the ambient air also is affected by the air density. Thus, at the reduced densities and temperatures encountered at altitude (Figure 1), the watts loss which can be dissipated by an electric machine may change, and its rating at altitudes may be different from that at sea level.

Each of the heat-transfer processes is now considered individually, and its variation with density and temperature determined.

Forced Convection. The transfer of heat by the forced circulation of a gas or liquid is referred to as heat transmission by forced convection. In an electric machine the cooling air enters the machine at an ambient temperature Θ_{a1}, and in wiping the windings and core removes heat from these parts. The resultant increase in air temperature ("air rise") is denoted by Θ_{ar}. This process is shown graphically in Figure 2, where Θ_{s1} is the surface temperature of the windings or core of the machine and Θ_d is the temperature drop between the hot surface and the cooling medium ("surface drop").

The maximum allowable winding surface temperature is determined by the insulation used in the machine. Thus, if Θ_{s1}', Θ_d', and Θ_{ar}' denote values of surface temperature, surface drop, and air rise, respectively, at the point at which the ventilating air leaves the machine,

$$\Theta_{s1}' = \Theta_{a1}' + \Theta_{ar}' + \Theta_d' \text{ degrees centigrade} \quad (1)$$

Θ_{ar}' is a function of the weight flow of air through the machine and the watts loss taken away by this air. Thus,

$$\Theta_{ar}' = \frac{0.133\, q_{for}}{W} \quad (2)$$

where

q_{for} = watts loss dissipated by forced convection
W = weight flow of cooling air through machine, pounds per minute
$W = \rho Q$
ρ = density of cooling air at entrance to machine, pounds per cubic foot
Q = volume flow of cooling air at entrance to machine, cubic feet per minute

The surface drop at the exit of the machine is:

$$\Theta_d' = \frac{q_{for}}{C} \text{ degrees centigrade} \quad (3)$$

where

C = over-all thermal conductance between machine surface and cooling air, watts per degree centigrade

The thermal conductance C is a function of the density of the cooling air ρ, its velocity v past the surface being cooled, and the area of that surface A_1. It has been shown (reference 1) that for the turbulent flow of air in ducts

$$C \propto A_1 (\rho v)^{\alpha} \quad (4)$$

In an electric machine the velocity v is composed of two components: the axial velocity of the cooling air through the ducts of the machine v_a, and the peripheral velocity of the rotor v_p. Tests on d-c aircraft-type generators indicate that for ratios of axial to peripheral velocity approximately less than 2, the axial velocity can be neglected; whereas, for ratios greater than 2, the peripheral velocity can be neglected. In the practical case of self-ventilated and separately ventilated aircraft generators, the former type usually has a ratio of axial to peripheral velocity well below 2, and the latter type has a ratio well above 2. Hence, the transition range need not be studied closely in the present investigation.

The axial velocity v_a is:

$$v_a = \frac{144Q}{A_d} \text{ feet per minute} \quad (5)$$

where

A_d = total area of ducts through which the cooling air flows, square inches

Thus, from equations 4 and 5 and the afore-mentioned assumptions,

$$C_{self} \propto A_1 v_p^{\alpha} \rho^{\alpha} = \frac{1}{k_1} \rho^{\alpha} \tag{6}$$

$$C_{sep} \propto A_1 \left(\rho \frac{144Q}{A_d}\right)^{\alpha} \propto A_1 \left(\frac{144}{A_d}\right)^{\alpha} W^{\alpha} = \frac{1}{k_2} W^{\alpha} \tag{7}$$

where k_1 and k_2 are constants for any given machine operating at constant speed, and C_{self} and C_{sep} are the over-all thermal conductances for self-ventilated

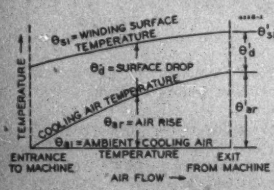


Figure 2. Temperature–air-flow diagram of a single-end axially ventilated electric machine

and separately ventilated machines, respectively.

In smooth ducts, $\alpha = 0.8$; in rough ducts, α may vary from 0.5 to 1.0, depending on the degree of roughness. On one aircraft-type d-c generator the use of an exponent of 0.5 checked test data.

Substitution of equations 2, 3, 6, and 7 into equation 1 gives:

Self-ventilated:

$$q_{tor} = \frac{\theta_{si}' - \theta_{ai}}{\frac{0.133}{W} + \frac{k_1}{\rho^{\alpha}}} \text{ watts} \tag{8}$$

Separately ventilated:

$$q_{tor} = \frac{\theta_{si}' - \theta_{ai}}{\frac{0.133}{W} + \frac{k_2}{W^{\alpha}}} \text{ watts} \tag{9}$$

Hence, if θ_{si}', θ_{ai}, ρ, and W are known at a given altitude, the watts loss which can be removed by forced convection at that altitude can be found if k_1, k_2, and α are known. These constants can be determined from sea-level tests on the machine.

Free Convection. The transfer of heat by the natural circulation of a gas, caused by a nonuniform temperature (and hence density) variation within the gas, is referred to as heat transmission by free convection.

The heat transferred from a horizontal cylinder in air is

$$q_{free} = 1.83 \times 10^{-4} A_2 p^{0.5} \frac{(\theta_{s2} - \theta_{a2})^{5/4}}{L^{1/4}} \text{ watts} \tag{10}$$

where

q_{free} = watts loss by free convection

A_2 = area of surface subject to free convection, square inches

p = atmospheric pressure, inches of mercury

θ_{s2} = convecting surface temperature, degrees centigrade

θ_{a2} = ambient air temperature for free convection, degrees centigrade

$L = \frac{L_h L_v}{L_h + L_v}$, feet

L_h = horizontal length of cylinder, feet

L_v = vertical height of cylinder, feet

The watts dissipated by free convection at any altitude therefore can be calculated from equation 10, since all factors are known. The surface temperature can be determined from sea-level tests. Tests taken under actual altitude conditions have indicated that the frame temperature remains essentially constant at various altitudes for the same maximum internal surface temperature, unless there are large changes in the heat dissipated from the frame of the machine.

It should be noted that the watts dissipated by free convection vary as the 0.5 power of the atmospheric pressure.

Radiation. Radiation is the method of heat transmission by which heat energy is transferred from one body to another through a transparent medium with no change in the temperature of the medium. When the area of the radiating body is small compared with that of its surroundings, the watts dissipated by radiation are:

$$q_R = 0.00375 \epsilon A_3 \left[\left(\frac{\theta_{s3}}{100}\right)^4 - \left(\frac{\theta_{a3}}{100}\right)^4\right] \text{ watts} \tag{11}$$

where

q_R = watts dissipated by radiation

ϵ = emissivity of the surface of the radiating body (0.9 for a body covered with a nonmetallic paint)

A_3 = area of radiating surface, square inches

θ_{s3} = radiating surface temperature, degrees centigrade absolute

θ_{a3} = ambient air temperature or temperature of surrounding bodies (if close enough) for radiation, degrees centigrade absolute

The preceding equation shows that the watts dissipated by radiation are independent of air density or pressure and, hence, of altitude for constant θ_{s3} and θ_{a3}. The same statements concerning these temperatures apply to this case as to the case of free convection.

Conduction. The heat transferred between two bodies by the conduction process is directly proportional to the conductivity of the transmitting medium, its area, and the temperature difference between the two bodies, and inversely proportional to the length of path. In an electric machine heat is conducted through its mounting, the direction of the transfer depending on the relative temperature of the two bodies. This heat transfer is difficult to calculate, since the length of path and the temperature difference are not accurately known. However, it is not affected by air density or temperature, provided the temperature of machine and mounting remain constant. Measurements of these temperatures must be made to determine the direction of heat flow, and the results obtained used to temper the calculations of total heat transferred by the other three processes. If heat is removed from the machine it can be neglected and used as a "safety factor;" if it is added, an estimate of the quantity added may be necessary.

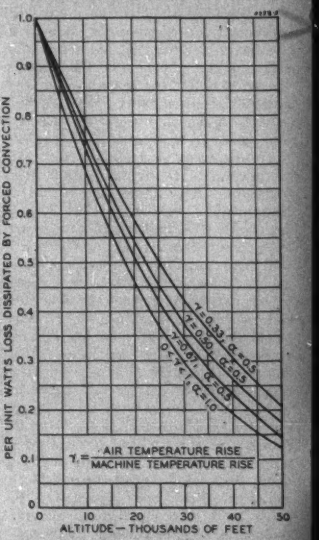


Figure 3. Effect of altitude on the watts loss dissipated by forced convection from a self-ventilated direct engine-driven aircraft generator

Constant maximum generator-winding surface temperature—140 degrees centigrade
Constant engine-accessory-compartment temperature—38 degrees centigrade

SUMMARY OF HEAT-TRANSFER EQUATIONS

$$q_{tot} = q_{tor} + q_{free} + q_R \text{ watts} \tag{12}$$

Self-ventilated:

$$q_{tor} = \frac{\theta_{si}' - \theta_{ai}}{\frac{0.133}{W} + \frac{k_1}{\rho^{\alpha}}} \text{ watts} \tag{8}$$

Separately ventilated:

$$q_{tor} = \frac{\theta_{si}' - \theta_{ai}}{\frac{0.133}{W} + \frac{k_2}{W^{\alpha}}} \text{ watts} \tag{9}$$

$$q_{free} = 1.83 \times 10^{-4} A_2 p^{0.5} \frac{(\Theta_{e1} - \Theta_{a2})^{5/4}}{L^{1/4}} \text{ watts} \quad (10)$$

$$q_R = 0.00375 \epsilon A_2 \left[\left(\frac{\Theta_{s2}}{100} \right)^4 - \left(\frac{\Theta_{a2}}{100} \right)^4 \right] \text{ watts} \quad (11)$$

Air Flow in Electric Machines

All the terms in the heat-transfer equations have been discussed, except the weight flow of the air used to cool the machine W. This quantity varies with altitude in a manner which depends on the type of ventilation employed. In the case of aircraft equipment, two types of machine are used: the enclosed self-ventilated machine, where the cooling air is circulated by a fan integral with the machine; and the enclosed separately ventilated machine, where the cooling air is picked up by an air scoop on the airplane and forced through the machine by the ramming pressure obtained from the airplane's motion. Single-end axially ventilated machines are discussed here, as this is the type in most common use on the equipment considered in this paper.

When the friction pressure drop of the air in flowing through the passages of a machine is neglected (a good assumption for small machines), the equation governing the air flow through a machine is:

$$H = \frac{p}{5.2} \left[\beta_m \frac{v_m^2}{2g} + \beta_n \frac{v_n^2}{2g} + \dots \right] \text{ inches of water}^* \quad (13)$$

where

H = pressure head available for forcing cooling air through machine, measured at entrance to machine, inches of water

$\beta_m \frac{v_m^2}{2g}, \beta_n \frac{v_n^2}{2g}, \dots$ = loss in pressure at contractions, expansions, bends, and so forth, of the air-flow path, measured in velocity heads of air

Since

$$v_m, v_n, \dots = \frac{144Q}{A_m}, \frac{144Q}{A_n}, \dots$$

$$H = \frac{Q^2 p}{58} \left[\frac{\beta_m}{A_m^2} + \frac{\beta_n}{A_n^2} + \dots \right] \quad (14)$$

where

$A_m, A_n, \dots$ = areas at changes in path section, square inches

The bracketed expression is a constant for any machine and may be called an "air resistance," R. Hence,

$$Q = \sqrt{\frac{58H}{\rho R}}, \text{ cubic feet per minute} \quad (15)$$

*This equation assumes that the air density is constant throughout the machine. Because of the air temperature rise this is not strictly true. However, the simplicity obtained by assuming a constant density warrants its use. For more accurate calculations an average air density may be used rather than the value at the machine entrance.

The weight flow of cooling air, therefore, is:

$$W = \rho Q$$

$$W = \sqrt{\frac{58H\rho}{R}}, \text{ pounds per minute} \quad (16)$$

This equation defines the weight of cooling air flowing through the machine for a given pressure head H. This pressure head will vary with altitude, depending on whether the machine is self-ventilated or separately ventilated by the methods discussed previously.

The pressure head developed by a fan revolving at constant speed varies directly with the air density. Therefore, in a self-ventilated machine the weight flow of air is directly proportional to the air density (equation 16).

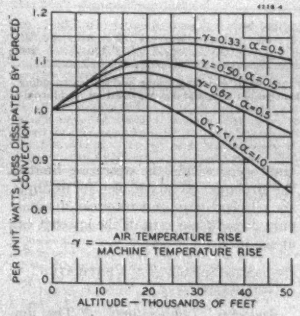


Figure 4. Effect of altitude on the watts loss dissipated by forced convection from a separately ventilated direct engine-driven aircraft generator

Constant maximum generator-winding surface temperature—140 degrees centigrade
Constant ramming-head cooling-air pressure
Cooling-air properties taken from Figure 1

For a separately ventilated machine employing an air scoop, the head H will depend on the airplane's speed–altitude characteristics. For a constant angle of attack the lift on an airplane wing is proportional to ρV^2, where ρ is the air density, and V is the velocity of the airplane relative to the air. Since a certain minimum lift is necessary to support the airplane, the minimum ρV^2 must remain constant, regardless of altitude. However, the pressure head in inches of water developed in the air scoop is directly proportional to ρV^2 (neglecting losses); hence the minimum air-scoop pressure head is independent of altitude for a separately ventilated generator. From equation 16 it can be seen that the minimum weight flow of air is thus proportional to the square root of the air density and therefore decreases with altitude, but not so rapidly as in the self-ventilated machine, where the decrease was directly proportional to the air density.

Application of Fundamental Analysis to the Determination of the Altitude Ratings of Rotating Electric Machines in Aircraft

The fundamental equations for heat transfer in rotating machines will be used now to determine the rating of electric machines under varying altitude conditions. The specific cases of self-ventilated and separately ventilated direct engine-driven d-c generators will be chosen for this discussion, each generator being considered separately. These generators are overhung from the back end of the aircraft engine. The self-ventilated generator secures its cooling air from the space back of the engine, known as the engine-accessory compartment; and the separately ventilated machine secures its cooling air from the atmosphere external to the airplane.

The general approach to the problem of altitude ratings is:

1. The determination of the ambient-temperature and air-flow conditions for each type of generator.

2. The calculation of the total watts loss which can be removed by the heat-transfer processes already discussed (heat transfer by conduction will be neglected) at the altitude at which the rating is desired.

3. The determination of the current, and hence the rating of the machine, corresponding to the total watts loss found in step 2 from a curve of watts loss of the machine as a function of its line current.

Enclosed Self-Ventilated Generator

Ambient Temperatures. The ambient temperature of the cooling air Θ_{a1} of a self-ventilated generator is that of the engine-accessory compartment. Tests have shown that this temperature is independent of altitude. Present information indicates that a minimum compartment temperature of 38 degrees centigrade and a maximum of 65 degrees centigrade may be expected. This ambient temperature is also the temperature to be used in calculating the heat transfer by free convection, Θ_{e1}.

The generator frame will radiate to or acquire heat from surrounding objects, depending on the relative temperature of the bodies involved. This transfer will remain substantially independent of altitude.

Air Flow. Previous equations have shown that the weight flow of air W through a self-ventilated generator is directly proportional to the air density and therefore decreases with altitude.

An inspection of equations 8, 10, and

11 now shows that the watts loss which may be dissipated by a self-ventilated generator, for a constant maximum-allowable surface temperature, decreases with increase in altitude. All quantities in these equations are constant except the air flow W, the air pressure p, and the air density ρ, all of which decrease with altitude. The reduction in rating depends on the relative proportions of q_{fw}, q_{free}, and q_R acting to cool the generator. Table I shows the per cent watts loss dissipated by each of the three heat-transfer processes at an altitude of 36,000 feet as compared with the dissipation at sea level (taken as 100 per cent). For example, if the generator could dissipate all of its loss by radiation alone, its rating would be independent of altitude, since q_R is independent of air density and pressure. In any actual application all processes will enter, but the watts dissipated by forced convection will be at least 80 per cent of the total for the lightweight high-output generators now used in the modern airplane and therefore will be the limiting feature.

Table I

Comparison of the Watts Loss Dissipated From Self-Ventilated Direct Engine-Driven Aircraft Generators Employing Different Proportions of Heat-Transfer Processes in Their Cooling

Per Cent of Total Watts Dissipated at Sea Level*			Per Cent of Sea-Level Watts Dissipated at 36,000 Feet*			
By Forced Convection $\gamma = 0.67, \alpha = 0.5$	By Free Convection	By Radiation	By Forced Convection $\gamma = 0.67, \alpha = 0.5$	By Free Convection	By Radiation	Total
100	0	0	27	0	0	27
0	100	0	0	47	0	47
0	0	100	0	0	100	100

* Maximum generator-winding surface (140 degrees centigrade), generator-frame surface, surrounding object, and engine-accessory-compartment (38 degrees centigrade) temperatures are constant for all comparisons.

Figure 3 shows the reduction in the watts loss that may be dissipated by forced convection in a self-ventilated generator, as a function of altitude, for constant maximum surface temperature and constant generator speed. Curves are plotted for various values of α in equation 8, and for various ratios of air rise to machine temperature rise at sea level γ. In self-ventilated machines this latter ratio is usually greater than 0.5.

After the total watts loss which can be dissipated by the three processes of heat transfer at a given altitude has been calculated, the new current rating of the generator at that altitude is found from the curve giving the generator line current as a function of its watts loss. This curve is approximated by a constant, representing the no-load losses of the machine plus a term which is a function of the square of the line current.

If the watts which can be dissipated at the operating altitude of the airplane are less than the no-load losses, the machine cannot even maintain its voltage at no load. Figure 3 shows that the self-ventilated generator thus has a "ceiling" of operation at which point the machine can dissipate its no-load losses only and can carry no load current without exceeding its maximum allowable temperature. Since the no-load losses of a lightweight high-output generator may be one quarter to one third of its total losses when carrying rated current, this ceiling may occur within the operating limit of the airplane. At 35,000 feet, for example, the self-ventilated generator can dissipate only 25 to 35 per cent of the losses it can at sea level.

Enclosed Separately Ventilated Generator

Ambient Temperatures. The ambient temperature of the cooling air θ_{a1} of a separately ventilated generator is that of the air outside of the airplane (neglecting a small temperature rise of the air at the entrance to the air scoop due to its compression). The Air Corps standard atmospheric air temperature decreases with altitude at a rate of -2 degrees centigrade for every 1,000-foot increase in altitude (Figure 1). The ambient temperatures for free convection and radiation remain the same as for the self-ventilated generator.

Air Flow. The minimum ramming-head cooling-air pressure available at the air scoop of an airplane is independent of altitude. From equation 16, therefore, the minimum weight flow of air in a separately ventilated generator is proportional to the square root of the air density.

Equations 10 and 11 show that the same watts loss is dissipated by free convection and radiation in the case of the separately ventilated generator as for the self-ventilated machine.

Figure 4 shows the variation in the watts loss that may be dissipated by a separately ventilated generator for constant ramming-head cooling-air pressure, constant maximum surface temperature, and constant generator speed. Curves are plotted for various values of α in equation 9 and for various ratios of air rise to machine temperature rise at sea level γ.

After determining the total watts loss which can be dissipated by the three processes of heat transfer, the altitude rating of the generator can be found from the curve of watts loss as a function of line current, as was done for the self-ventilated generator.

From Figure 4 and equations 10 and 11 it is apparent that a separately ventilated generator, which obtains its cooling air from an air scoop on the airplane, maintains and may even increase its sea-level rating at practically all altitudes within the operating range of present-day aircraft. In the case of the separately ventilated generator, the reduction in cooling-air ambient temperature offsets the decrease in weight flow of cooling air. Also, due to the constancy of the ramming-head cooling-air pressure of the separately ventilated generator, the weight flow of cooling air decreases only with the square root of the air density. In the self-ventilated gen-

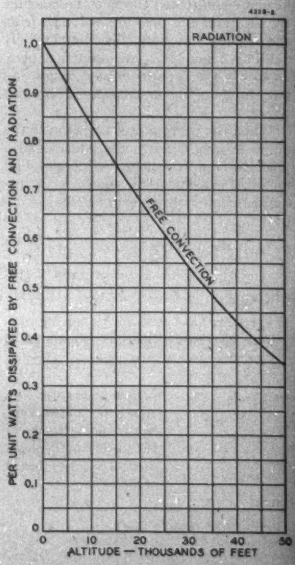


Figure 5. Effect of altitude on the watts loss dissipated by free convection and radiation from self- and separately ventilated direct engine-driven aircraft generators

Constant generator frame surface, engine-accessory compartment, and surrounding object temperatures

erator the weight flow decreases directly with the air density.

Conclusions

A. Figure 3 shows that the rating of an enclosed self-ventilated direct engine-driven d-c aircraft generator decreases rapidly with altitude, and may have a "ceiling" within the altitude range of the airplane on which it is mounted. This ceiling is the point at which the generator will just dissipate its no-load losses without overheating.

B. Figure 4 shows that the rating of an enclosed separately ventilated direct engine-driven d-c aircraft generator, obtaining its cooling air from an air scoop mounted on the airplane, remains essentially independent of altitude—the rating increasing slightly over its sea-level value up to 20,000 feet and then decreasing again.

C. Sea-level tests can be taken, by means of which the rating of a given generator at a given altitude can be determined if ambient conditions at that altitude are known (see appendixes).

D. The analysis presented in this paper can be used to determine the air-flow requirements necessary to obtain a given rating from a given generator at any desired altitude (see appendixes).

E. The results of this analysis can be applied to the determination of the altitude heating and rating of types of electric apparatus other than aircraft generators, if the assumptions made here are critically reviewed and adapted to meet the new conditions.

F. While the effect of brush and commutator heating on limiting the altitude rating of a generator has not been discussed, this problem can be analyzed using the formulas applying to a self-ventilated machine, since whether the machine is self- or separately ventilated the peripheral velocity of the commutator is large compared with the axial velocity of the cooling air (see *Forced Convection* under *Fundamental Analysis*).

G. This paper presents some of the fundamentals of the problem of altitude rating of electric machines and has proposed tests for its determination. It is hoped that future test data, obtained both in altitude chambers and under actual operating conditions, will be correlated and used to modify and expand the analysis where necessary.

Appendix A. Sea-Level Tests and Altitude Performance Calculations for Generators Designed for Aircraft Applications

The tests proposed here are based on the assumption that the point at which the maximum-allowable surface temperature Θ_{s1} is measured at sea level remains the hottest point in the machine as the load on the machine is varied. Tests on aircraft-type generators have indicated that this assumption is correct. In the proposed tests the generator mounting should be insulated thermally from the test stand on which it is mounted, in order to eliminate the effects of conduction. It is also assumed that the outer surface of the generator remains essentially at constant temperature for a constant maximum internal surface temperature. This assumption has been checked by altitude-chamber tests.

A. Preliminary Tests

These preliminary sea-level tests determine the weight flow of cooling air forced through the generator for various ramming-head pressures at the entrance to the generator cooling system, the watts loss of the machine for various line currents, and the value of the exponent α in equations 8 and 9.

1. Measure the volume flow of air through the generator for various inlet ramming-head air pressures. Set up the generator as a separately ventilated machine and operate at minimum rated speed. Vary the volume flow from a value at which the ratio of the axial velocity of the cooling air to the peripheral velocity of the rotor is approximately 2, to a value at which this ratio is approximately 4.

2. Plot a curve of weight flow of air as a function of the ramming-head pressure of cooling air from the results obtained in section *A*-1.

3. Calculate or determine from dynamometer tests the watts loss of the generator as a function of its line current with the generator operating at its minimum rated speed and rated maximum-allowable surface temperature. Plot a curve of total watts loss as a function of line current.

4. Take a series of heat runs on the generator at minimum rated speed at various inlet ramming-head air pressures, covering the range of pressures used in section *A*-2. At each pressure vary the generator load current until the temperature of the hottest surface in the machine is equal to the maximum-allowable surface temperature. Keep the generator ambient temperature Θ_{a1} at the same value as is expected during actual operation.

5. Calculate the watts dissipated by free convection and radiation in each of the runs of section *A*-4 from equations 10 and 11. Subtract these values from the total watts dissipated in each of the runs, and plot a curve of watts dissipated by forced convection as a function of inlet ramming-head air pressure.

6. Rewrite equation 9 as:

$$\log k_2 + (1-\alpha)\log W = \log\left[\frac{W(\Theta_{s1}'-\Theta_{a1})}{q_{fcr}} - 0.133\right]$$

Plot W as a function of

$$\left[\frac{W(\Theta_{s1}'-\Theta_{a1})}{q_{fcr}} - 0.133\right]$$

on log–log paper for various values of inlet ramming-head air pressure. Select a value of this pressure and find q_{fcr} from the curve of section *A*-5 and W from the curve of section *A*-2 for this pressure. Using these values of W and q_{fcr}, plot one point of the aforementioned curve. Repeat, using a different pressure.

7. Obtain the slope of the curve of section *A*-6 and calculate α, knowing that this slope is equal to $(1-\alpha)$.

B. Self-Ventilated Generator

To find the altitude rating of a self-ventilated aircraft generator, proceed as follows:

1. Take a heat run at minimum rated speed at such a line current that the temperature of the hottest surface in the machine is equal to the maximum-allowable surface temperature for the generator insulation. Take this heat run in an ambient temperature equal to the expected engine-accessory-compartment temperature at the altitude at which the generator is to be rated.

2. Measure the volume flow of air Q through the machine under the ambient conditions of section *B*-1, and calculate the weight flow of cooling air through the machine.

3. From the watts loss-current curve of section *A*-3, determine the total watts loss of the machine at the load of section *B*-1.

4. Calculate the watts dissipated by free convection and radiation in the heat run of section *B*-1 from equations 10 and 11.

5. Determine the watts dissipated by forced convection in the heat run of section *B*-1 by subtracting the watts dissipated by free convection and radiation from the total watts dissipated.

6. Calculate k_1 in equation 8, using temperatures and the weight flow of air found in sections *B*-1 and *B*-2, the value of α found in section *A*-7, and the value of q_{fcr} found in section *B*-5.

7. Calculate the total watts dissipated at the altitude at which the generator rating is to be determined from equations 8, 10, and 11. Use values of air density and pressure, and engine-accessory-compartment temperature at the given altitude. The weight flow of air in a self-ventilated generator is directly proportional to the air density. Use values of Θ_{s1}', Θ_{s2}, Θ_{a2}, Θ_{a1}, Θ_{a3}, and Θ_{a2} from the heat run of section *B*-1.

8. Determine the altitude current rating of the generator by entering the watts loss-current curve of section *A*-3 with the total watts dissipated as calculated in section *B*-7

C. Separately Ventilated Generator

To find the altitude rating of a separately ventilated generator, proceed as follows:

1. Determine the minimum ramming-head cooling-air pressure in inches of water available at the entrance to the generator cooling cap at the altitude at which the rating of the generator is to be found.

2. Determine the watts loss that can be dissipated by forced convection by the generator with this ramming-head pressure at sea level from the curve of section *A*-5.

3. Calculate the value of k_2 from equation 9, using the watts loss found in section *C*-2, the weight flow of air from section *A*-2 (correcting for any difference between the cooling-air temperatures of the runs in sections *A*-2 and *C*-2 in determining the weight flow), the temperatures from the heat runs of section *A*-4, and the value of α from section *A*-7.

4. Calculate the total watts dissipated at the altitude at which the generator rating is to be determined from equations 9, 10, and 11. Use values of air pressure and cooling-air temperature and density from Figure 1. The weight flow of cooling air in a separately ventilated generator is proportional to the square root of the cooling-air density. Use values of Θ_{s1}', Θ_{s2}, Θ_{a2}, Θ_{a1}, and Θ_{a3} from the heat run of section *A*-4, corresponding to the minimum ramming-head cooling-air pressure of section *C*-1.

5. Determine the altitude current rating of the generator by entering the watts loss-current curve of section *A*-3 with the total watts dissipated as calculated in section *C*-4.

Appendix B. Determination of the Altitude Rating or the Required Ramming-Head Pressure of a Separately Ventilated Aircraft Generator

By the use of certain simplifying assumptions the current which a separately ventilated generator will deliver at altitude, or, conversely, the ramming-head pressure required to obtain a given current at altitude, can be determined from a single sea-level heat run on the generator.

In the following analysis the value of α in equation 9 is assumed to be unity; the effects of convection, radiation, and conduction in cooling the machine are neglected; and the watts loss of the machine is assumed to vary as the square of the generator line current. Assuming α to be unity gives a

higher value of the watts which may be dissipated by forced convection than is actually the case, but the omission of the watts dissipated by other processes offsets the effect of this first assumption. Finally, in a separately ventilated generator, the I^2R losses are usually at least three to four times the fixed losses, so that at the generator's normal rating the total losses vary approximately as the square of the current.

From equations 7 and 16, therefore:

$$q_{fcn} = K_4 I^2 = \frac{W}{0.133 + K_3}(\Theta_{s1}' - \Theta_{a1})$$

$$= \frac{\sqrt{58\rho H}}{0.133 + K_3}(\Theta_{s1}' - \Theta_{a1})$$

$$I = K_4 \sqrt[4]{\rho H}(\Theta_{s1}' - \Theta_{a1})^{\frac{3}{4}}$$

If we let the subscripts A denote the value of a quantity at any altitude, and 0 denote the value at sea level, then:

$$I_A = I_0 \sqrt[4]{\left(\frac{\rho_A}{\rho_0}\right)\left(\frac{H_A}{H_0}\right)\left[\frac{(\Theta_{s1}' - \Theta_{a1})_A}{(\Theta_{s1}' - \Theta_{a1})_0}\right]^3} \text{ amperes} \quad (17)$$

or:

$$H_A = H_0 \left(\frac{\rho_0}{\rho_A}\right)\left(\frac{I_A}{I_0}\right)^4 \left[\frac{(\Theta_{s1}' - \Theta_{a1})_0}{(\Theta_{s1}' - \Theta_{a1})_A}\right]^3 \text{ inches of water} \quad (18)$$

From a single sea-level heat run, then, I_0, ρ_0, H_0, and $(\Theta_{s1}' - \Theta_{a1})_0$ are determined. Knowing these, and the density, inlet air temperature, and allowable hot-spot temperature at the altitude at which the generator is to operate, the current which the machine will deliver without exceeding its temperature rise for a given ramming-head cooling-air pressure can be calculated from equation 17. Also, the ramming-head pressure required for a given current rating can be calculated from equation 18.

Altitude-chamber tests have been taken, and altitude ratings and pressure heads calculated from equations 17 and 18 have checked almost exactly with test values.

For a more fundamental calculation of altitude performance, the methods of Appendix A should be used.

Nomenclature

A_1 = area of machine surface for forced convection, square inches

A_2 = area of machine surface for free convection, square inches

A_3 = area of machine surface for radiation, square inches

A_d = total area of machine ducts through which cooling air flows, square inches

β_m, β_n = numerical constants depending on type of change of air-flow section

C_{self} = over-all thermal conductance between machine surface and cooling air for self-ventilated machines, watts per degree centigrade

C_{sep} = over-all thermal conductance between machine surface and cooling air for separately ventilated machines, watts per degree centigrade

ρ = density of cooling air at entrance to machine, pounds per cubic foot

ϵ = emissivity of radiating surface

γ = air temperature rise

g = gravitational constant, feet per minute squared

H = pressure head available for forcing cooling air through machine, inches of water

$L = \frac{L_h L_v}{L_h + L_v}$, feet

L_h = horizontal length of machine for free convection, feet

L_v = vertical height of machine for free convection, feet

p = atmospheric pressure, inches of mercury

q_{fcn} = watts loss dissipated by forced convection

q_{free} = watts loss dissipated by free convection

q_R = watts loss dissipated by radiation

Q = volume flow of cooling air through machine measured at entrance, cubic feet per minute

R = resistance of machine to flow of cooling air

Θ_{a1} = ambient air temperature for forced convection, degrees centigrade

Θ_{a2} = ambient air temperature for free convection, degrees centigrade

Θ_{a3} = ambient air temperature for radiation, degrees centigrade absolute

Θ_{cr} = cooling-air temperature rise (air rise) degrees centigrade

Θ_d = temperature difference between machine surface and cooling air (surface drop), degrees centigrade

Θ_{s1} = machine surface temperature for forced convection, degrees centigrade

Θ_{s2} = machine surface temperature for free convection, degrees centigrade

Θ_{s3} = machine surface temperature for radiation, degrees centigrade absolute

v = velocity of cooling air past machine surface being cooled, feet per minute

v_a = axial velocity of cooling air through ducts of machine, feet per minute

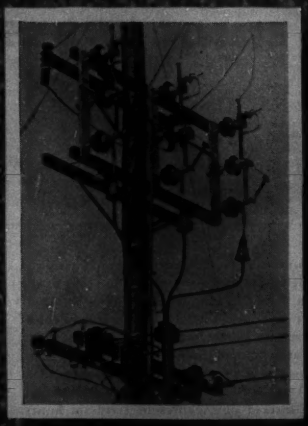
v_p = peripheral velocity of rotor, feet per minute

W = weight flow of cooling air through machine, pounds per minute

Primed quantities are values measured at the cooling-air exit of the machine.

Reference

1. The Basic Laws and Data of Heat Transmission, W. J. King. *Mechanical Engineering*, March 1932, pages 190–4; April 1932, pages 275–9 and page 296; May 1932, pages 347–53; June 1932, pages 410–14, and page 426; July 1932, pages 492–7; August 1932, pages 560–5.



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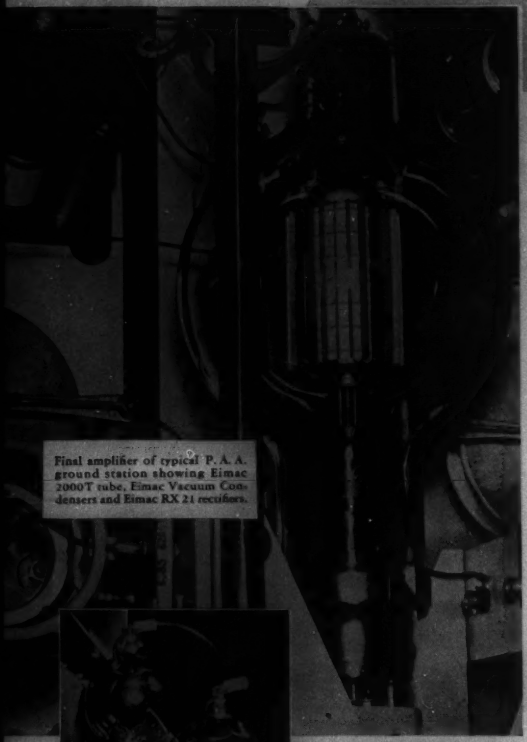

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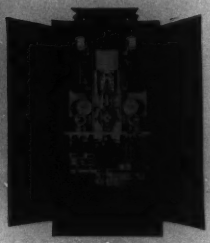

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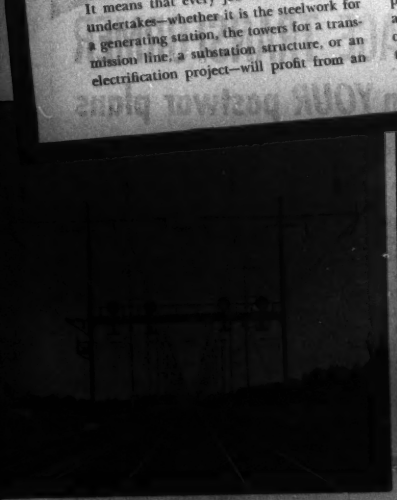

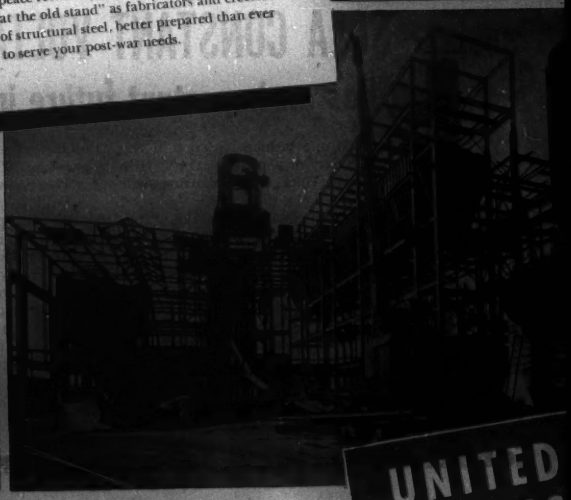

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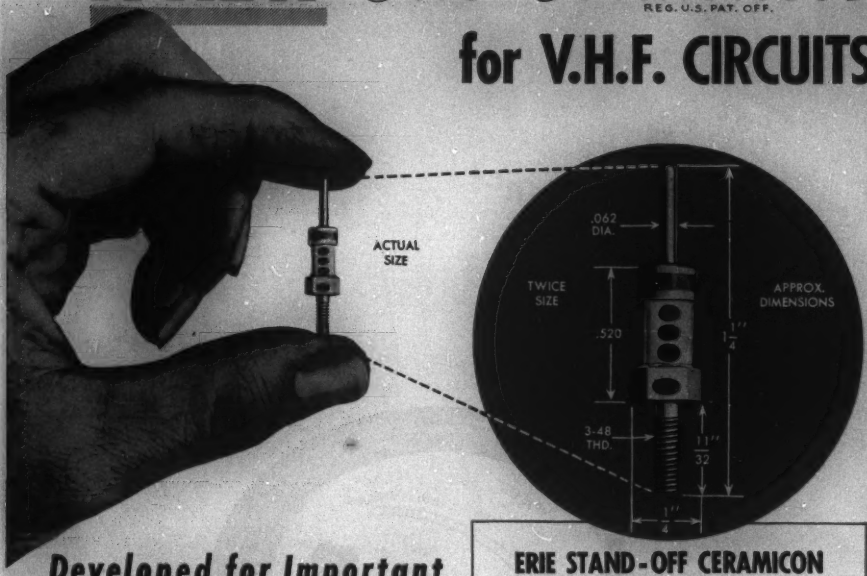

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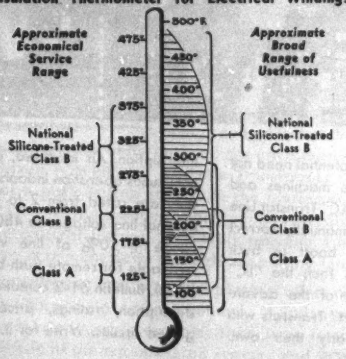
We have combined these new Silicone resins with glass textiles and Micaglas to allow greater use of the heat-resistant qualities of glass and mica.

An idea of the tremendously important result gained is seen in the fact that insulation so treated remains flexible under 482° F. for 50 hours. At continuous 270° F. for ninety days National Silicone-treated coils showed only slight aging. The conventional varnish used in Class B coils of the same kind in the same test was completely disintegrated.

So important is this new technique to operators of rotating electrical machines that it ranks in importance with the introduction of asbestos and fiberglas as a second great step forward in the battle against heat damage.

Insulation Thermometer for Electrical Windings



Much Longer Life for Over-Heated Electric Windings

Obviously, National coils insulated with Silicone-treated Fiberglas or Micaglas offer relief to the operator who is compelled to overload his motors or to operate them in high ambient temperatures. Increased life and reduced coil trouble result. Where either continuous or intermittent heat at or somewhat above the upper limit of conventional Class B insulation causes trouble, National Silicone-treated insulation will vastly improve performance.

Note that Silicone does not affect the heat-resisting qualities of the materials with which it is used. It simply replaces less heat-stable bonding agents and fillers whose low heat-damage levels prevented utilization of the excellent properties of glass, mica, etc., at higher temperatures.

Please Note

Several limiting factors in the use of Silicone varnishes must be taken into consideration. Motor bearings are subject to heat damage. Electrical joints should be brazed rather than soldered. The copper in commutators and slip rings anneals at the curing temperature of Silicone varnishes.

Silicone varnishes should not be used indiscriminately. ***Because of factors other than heat, conventional varnishes may often be used advantageously.***

AVAILABILITY

National Silicone-bonded Fiberglas and Micaglas are already available in restricted quantities. National Silicone-treated sleeving, tubing and similar products are in production, but not yet in sufficient quantities for unlimited use. National Silicone Fiberglass and Micaglas insulated coils can now be produced in limited quantities. If heat is causing persistent trouble give us the facts.

Copyright 1944, National Electric Coil Company, Columbus, Ohio

NATIONAL ELECTRIC COIL COMPANY
COLUMBUS, OHIO
ELECTRICAL ENGINEERS: MAKERS OF ELECTRICAL COILS AND INSULATION—
BLUEFIELD, W. VA.
REDESIGNING AND REPAIRING OF ROTATING ELECTRICAL MACHINES

When the Lights go On*

Here's the Remedy:

Dips and peaks in line potential need not disturb voltage-sensitive machines and devices. The AmerTran "LC" Transtat Line Voltage Compensators manually correct such fluctuations. They boost or buck voltage as needed. In fact, the "LC" Transtats combine most of the advantages of the famous "TH" Transtats with some that are peculiarly their own.

These advantages include lower cost per KVA of output and close control in increments as low as 0.2 volt without circuit interruption. Air insulated, designed for continuous operation indoors at full load, they are rated from 2 to 85 KVA, for nominal line voltages to 480, adjustment range ± 10% of line voltage. Also available for remote push-button control (LCM). Bulletin 51-2 contains a complete description, ratings, prices and suggested circuits. Write for it.

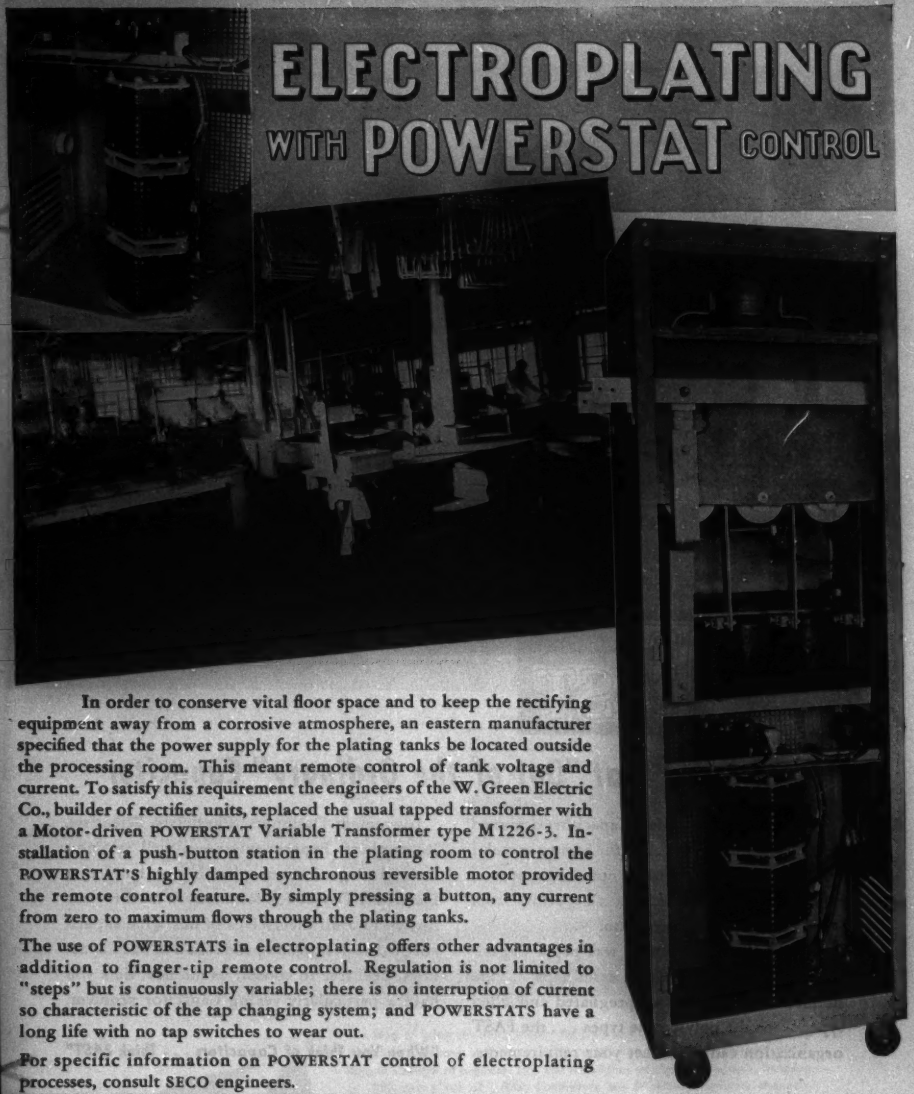
AMERICAN TRANSFORMER CO.
178 EMMET STREET, NEWARK 5, NEW JERSEY

* Reduces higher than rating line voltages, too. Swelling or sagging voltages are handled with equal ease by "LC" Transtat Line Voltage Compensators.

AMERTRAN

Pioneer Manufacturers of Transformers, Reactors and Rectifiers for Electronics and Power Transmission

ELECTROPLATING WITH POWERSTAT CONTROL



In order to conserve vital floor space and to keep the rectifying equipment away from a corrosive atmosphere, an eastern manufacturer specified that the power supply for the plating tanks be located outside the processing room. This meant remote control of tank voltage and current. To satisfy this requirement the engineers of the W. Green Electric Co., builder of rectifier units, replaced the usual tapped transformer with a Motor-driven POWERSTAT Variable Transformer type M1226-3. Installation of a push-button station in the plating room to control the POWERSTAT'S highly damped synchronous reversible motor provided the remote control feature. By simply pressing a button, any current from zero to maximum flows through the plating tanks.

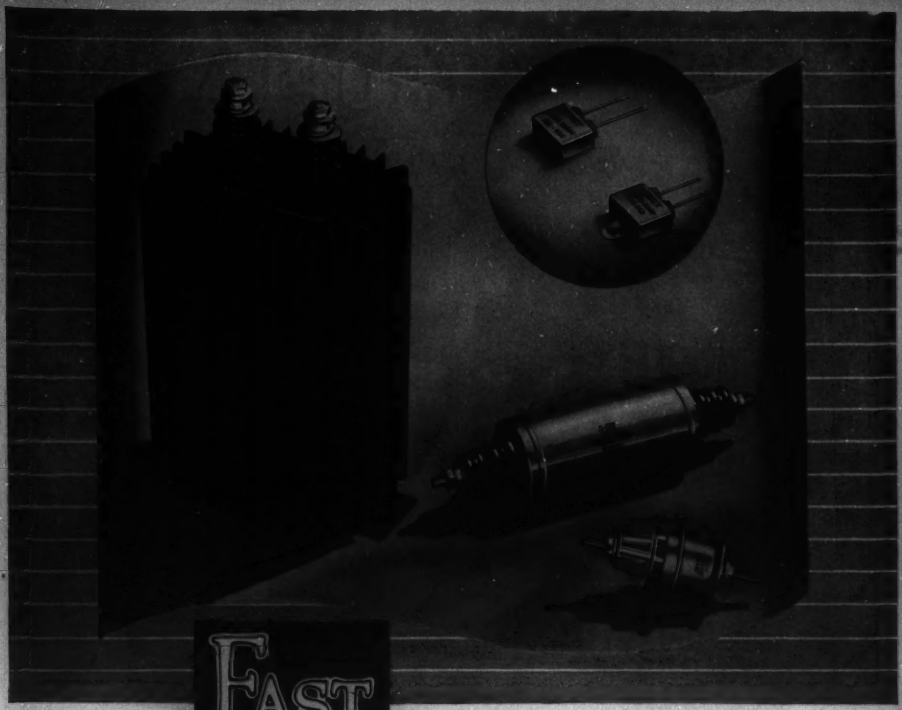
The use of POWERSTATS in electroplating offers other advantages in addition to finger-tip remote control. Regulation is not limited to "steps" but is continuously variable; there is no interruption of current so characteristic of the tap changing system; and POWERSTATS have a long life with no tap switches to wear out.

For specific information on POWERSTAT control of electroplating processes, consult SECO engineers.

Send for Bulletins 149 EE and 163 EE

SUPERIOR ELECTRIC CO., 245 LAUREL STREET BRISTOL, CONNECTICUT

SUPERIOR *Electric Company*



FAST

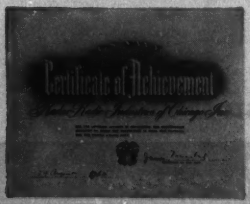
can build that "Out of the Ordinary" Capacitor

Pictured above are a few Capacitors designed for unusual operation . . . or for some particular application which requires not only a special container and terminals, but a departure from standard internal construction.

Whether it be the tubular wax paper Capacitor . . . the wax filled metal cased type . . . the hermetically-sealed oil impregnated and filled type . . . or the polystyrene types . . . the FAST organization can best meet your requirements.

Instrument Designers, Physicists, Scientists, Researchers, Experimenters—as well as Commercial Organizations planning to build that Electronic Device for tomorrow's market—are invited to avail themselves of our wide experience in the design and production of fine Capacitors. Feel free to consult us the next time you have a particularly vexing Capacitor problem.

"When You Think of Capacitors . . . Think FAST"



CERTIFICATE OF ACHIEVEMENT

It may be of interest to note this is the first time in the history of the United States Navy that any industry has been selected for a citation of honor and achievement. The John E. Fast organization is a member of this group.

JOHN E. FAST & CO.

Capacitor Specialists for a Quarter-Century

3125 North Crawford Avenue, Chicago 41

Canadian Representatives: Bensimon Engineering Works Reg'd. 2101 Bennett Avenue, Montreal, for Power Factor Correction J. R. Longstaffe, Ltd., 11 King Street, W., Toronto 1, for Special Applications

Alcoa Aluminum is Available

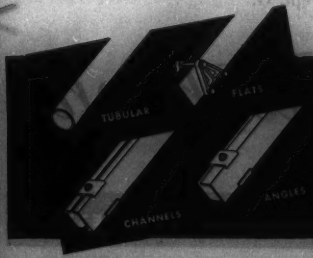
FOR BUS BARS AND FITTINGS

Now that the supply of aluminum exceeds the demands for military uses, Alcoa Aluminum bus bar shapes and fittings are again available. You can proceed with the extension and modernization work held up by previous restrictions.

Less labor is required to install aluminum bus bars. Their lighter weight makes handling and erection easier. Supports can be similarly lighter and more widely spaced. Buses can, therefore, often be installed without expensive reinforcement of structures.

Alcoa engineers will gladly help select conductors and fittings for your bus installations. Write ALUMINUM COMPANY OF AMERICA, 2149 Gulf Building, Pittsburgh 19, Pennsylvania.

The idea of using structural shapes for electrical conductors was originated by Aluminum Company of America; better ventilation and higher efficiency, rigidity and strength of a girder. This first installation of channel bus bars, installed in 1928, has a run of 1,600'. Conductors are 5" Alcoa Aluminum channels.



ALCOA
ALUMINUM

THE Telechron Pre-Selector shown here is an important development for post-war radios. It's low in cost — recommended for use with moderate-price receivers.

Buyers will like this easy-to-use Pre-Selector, with finger-tip control. Each of the 48 keys around the Telechron clock dial represents a 15-minute timing interval. Pulling out a key automatically turns the receiver on, at the pre-selected station, for 15 minutes—and off at the end of the period, unless the next key is pulled out also. Keys are automatically reset to OFF position after timing periods are passed.

A flick of the finger sets the keys around the large and legible clock face. There are no knobs to turn, no complicated settings, no difficult calculating. Settings can be made as much as 10 hours in advance.

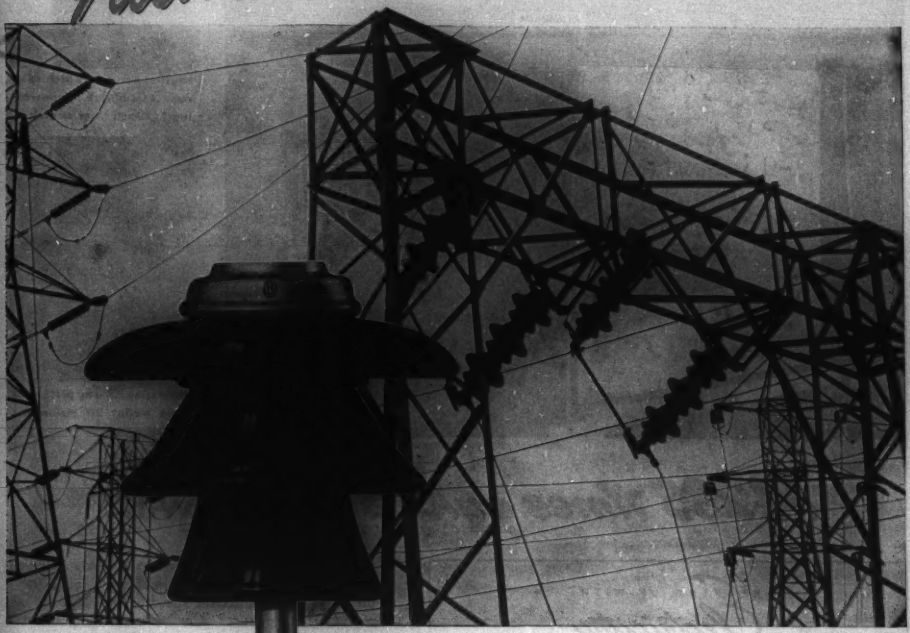
This Telechron Pre-Selector is only one of a full line of automatic timing and control devices which we can supply for post-war home appliances. All use the famous self-starting, synchronous Telechron motors and movements. For full information about Telechron timers, wire or write Automatic Control Division, Dept. G.

ANOTHER TELECHRON TIMER
THE TELECHRON SIGNAL TIMER
works on the alarm clock principle. It's used for range, radio, and other home appliances where on or off timing is needed. It has both switch and audible features. We also have regular clock movements for any size receiver.

Telechron
REG. U. S. PAT. OFF.

WARREN TELECHRON COMPANY • ASHLAND, MASSACHUSETTS

Present TESTS CANNOT PREDICT *Future* STATION INSULATOR SERVICE—



But You Can Rely Upon O-B's 30-Year Record

Specified M. & E. tests on a switch and bus insulator deal wholly with the present--present strength, present dielectric values. They tell you accurately what you have *now*. But "now" is only one important consideration in station insulation. Ten, twenty, thirty years from now represents service performance and can't be predicted reliably by any known set of tests or specifications.

Has O-B anything concrete to offer in the way of looking into the future? Just this: Thousands of O-B insulators have rounded out thirty years of station service and are still on the job. Big improvements have come about since these pioneers went to work. Today's designs have better reason for such performance.

It's a matter of actual record, gained from the longest station insulator history in the industry, that sound reliability is an integral part of O-B Insulation. You can't assure such future performance by any specifications or tests, but you can get it simply by writing "O-B" on your order.

Ohio Brass

2499-H

MANSFIELD, OHIO, U. S. A.

CANADIAN OHIO BRASS COMPANY, LIMITED
NIAGARA FALLS, ONTARIO

PICTURES COURTESY LABORATORY DIVISION, FRANKFORD ARSENAL

High-speed X-ray picture of cal. .30 bullet penetrating 1/2 inch thick armor

High-speed X-ray picture of same bullet 20 millionths of a second later

14,285 times quicker than a wink

KEEPING UP WITH *Electricity*

MAN-MADE HURRICANE BLOWS OUT ELECTRICITY. Engineers can now "blow out" electricity as easily as you extinguish the flame from your cigarette lighter. Circuit breakers built by Westinghouse unleash a 600-mile-an-hour blast of compressed air to snuff out powerful short-circuit arcs and prevent damage to vital electrical equipment on power lines. The hurricane of air can smother a 1,000,000-kilowatt electric arc in less than a hundredth of a second.

REPRESENTATIVES OF 257 PRE-WAR PROFESSIONS, businesses, and trades are now employed at the Westinghouse operated Naval Gun Plant at Louisville, Kentucky. Included are: former circus performers, several embalmers, a former professional hill-billy musician, and a pipe-organ builder. Despite their unusual peace-time occupations, all here have been able to learn the amazing high precision needed in making Naval guns.

A NEW GUNSIGHT LAMP that enables American gunners to aim *directly into the sun* and yet fire with deadly accuracy has been developed for the Army and Navy by Westinghouse Lamp Engineers. Former gunsight lamps allowed gunners to aim within only 15 degrees of the sun, leaving a dreaded "blind spot."

FREE . . . "Engineering Highlights of 1944"—a 32 page book, filled with interesting articles on new developments in electrical research and engineering in wartime. Write: Westinghouse Engineer (EE-124).

Westinghouse research engineers have developed an ultra-high speed X-ray tube that makes possible X-ray pictures, taken at the terrific speed of *one-millionth of a second.* These pictures show armor-piercing bullets penetrating ½ inch of solid steel armor plate.

The action is 10,000 times faster than any conventional X-ray—literally 14,285 times *quicker than a wink!*

Secret of this revolutionary X-ray is the new type tube that can handle a jolt of 2000 amperes, at 300,000 volts. This is applied in a flash by electrostatic condensers—creating a tremendous surge of *X-radiation.*

With this new X-ray, U.S. Army ballistic experts can "freeze" the image of a bullet, while it travels within a gun barrel at 2600 feet per second—or study the action of projectiles as they smash through armor plate.

When peace returns, this new example of Westinghouse *skill in research* will enable machine builders to study the strains in rapidly moving parts—improve performance and increase the life of peacetime products.

Westinghouse Electric & Manufacturing Company, Pittsburgh 30, Pennsylvania.

Westinghouse

PLANTS IN 25 CITIES OFFICES EVERYWHERE

TUNE IN: John Charles Thomas, Sunday 2:30, EWT, NBC
Ted Malone, Mon. Wed. Fri., 10:15 pm, EWT, Blue Network

Vinylite

When deliveries start again...

New car deliveries will prove that happier days are here again. Though they look like prewar models, they'll be better cars—improved in many ways. Harness-type wiring systems wrapped in VINYLITE plastic tape, for instance, will be far safer and more dependable than any former assemblies. This unique tape is used on the multiple circuit harnesses of almost every combat vehicle and truck that's built today.

VINYLITE plastic tape gives wiring harnesses 8-way protection. It is non-flammable, eliminating the fire hazard. It is non-oxidizing and permanently flexible; has high dielectric and high tensile strength; resists chemicals and abrasion. Moisture, oils, and grease find it practically immune to their deteriorating action.

But that's only part of the story. VINYLITE plastic tape revolutionizes the *production* of wiring harnesses. It is applied by standard wrapping procedures, and heat-sealed by baking for only 15 minutes, at 265 deg. F. No varnish is used. No additional baking—no cleaning of terminals. Production time cut from 24 hours to 24 minutes.

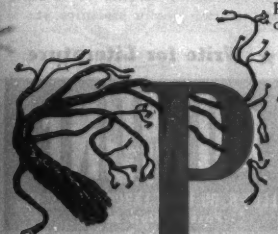
Besides their use as insulating tapes, VINYLITE plastics are available as extrusion materials for primary insulation, tubular jacketing, and conduits. Wherever used, they bring new economy and safety to the electrical wire and cable field. You will probably find them a real investment in connection with your own products, present or planned. Write for descriptive booklet 1-VR, "Vinylite Plastics for Wire and Cable Insulation."

BAKELITE CORPORATION

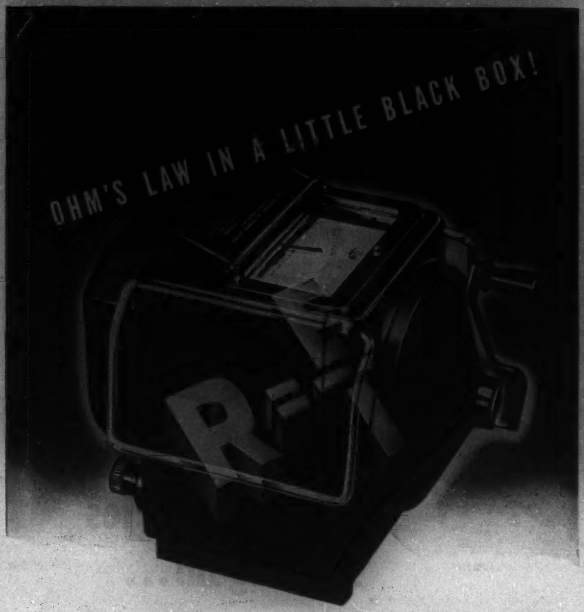
Unit of Union Carbide and Carbon Corporation

UCC

30 EAST 42ND STREET, NEW YORK 17, N.Y.



Plastics



. . . THE "MEGGER"* INSULATION TESTER

The dependability of the "Megger" Instrument for measuring electrical insulation resistance is like the constancy of Ohm's Law, on which principle it actually operates. This "Megger" method for testing insulation resistance is simple and remarkably accurate. The principle is precisely the same as it was forty years ago and yet it meets today's needs perfectly.

You will find the same ruggedness and dependability in U.S.-made "Megger" instruments that the electrical industry has known for so long a time.

Let us send you full details on various types and ratings. Ask for Bulletin 1685-EE.

* *Trade Mark Reg. U. S. Pat. Off.*

PRINCIPLE OF OPERATION

In what we term a cross-coil true ohmmeter, two coils are mounted in fixed relation to each other on the same pivot-and-jewel moving system in the field of a permanent magnet. "Current" flows in coil A and "potential" in coil B, and they are connected so that their respective torques oppose each other. Since there are no control springs, the opposing coils give a true ratio of E/I, and ohms (or megohms) are indicated directly by a pointer over a scale. The readings are independent of the voltage of the hand-driven d-c generator, because any change in the voltage affects both coils in the same proportion.

JAMES G. BIDDLE CO. 1211 ARCH ST. PHILA. 7, PA.

CATHODE-RAY *Oscillography*

★ You're probably losing time and money if you are without a cathode-ray oscillograph. We can prove it in most cases. In the plant, out in the field, in the laboratory, in servicing and maintenance—a DuMont cathode-ray oscillograph is a "must" instrument today.

DuMont offers a wide choice of types to meet all requirements. Here are typical uses: To check wave form and harmonic content. Also to check phase. Useful in checking power factor, welding cycle, relay and circuit breaker operation, etc. Used to check vibration, dynamic balancing of rotating parts, ignition, engine pressures, etc.

★ **Write for Literature**

DUMONT

ALLEN B. DU MONT LABORATORIES, INC.
Passaic, New Jersey

Cable Address: Wespaxlin, New York

The Art of Buying

ARC WELDING ELECTRODES HAS BEEN GREATLY SIMPLIFIED...

It used to be.. a puzzling situation — those electrodes with confusing trade names and trade numbers. Each manufacturer's identification system was different, each one had his own special name for electrodes. Thus, for example, one particular rod designated by American Welding Society as E-6012 had over twenty different trade names. And no two trade names were even vaguely similar. To a welder selecting a certain rod for a definite job these varying trade names were disconcerting. They had *no* connection with any standard welding classification. Unless he had previously used the rod or took time to check into its classification, he was at a loss to select the correct electrode.

..But now Allis-Chalmers has cut through this mass of confusion and greatly simplified the business of buying electrodes. Official *AWS classification numbers* have been adopted for Allis-Chalmers electrode identification. Thus *AWS E-6012* becomes *Allis-Chalmers E-6012* in the A-C electrode line. It's logical and practical. Correct selection is automatically assured.

Shop-tested and production-proven in A-C's own huge plants, these electrodes are available now at Allis-Chalmers welding dealers and district offices. Write for bulletin B6340. A 1780

ALLIS-CHALMERS

MILWAUKEE 1, WISCONSIN

HEADQUARTERS FOR WELDING EQUIPMENT

AMPAC A-C WELDERS

WELD-O-TRON D-C WELDERS

ALLIS-CHALMERS ELECTRODES

ARC WELDING ACCESSORIES

♪ *Tune in the Boston Symphony, Blue Network, every Saturday at 8:30 pm, EWT*

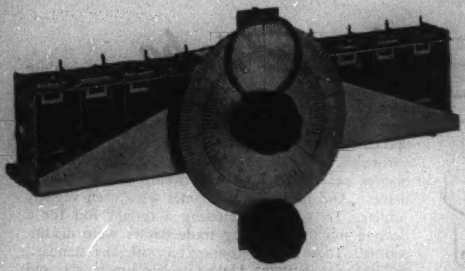
A NEW -*hp*- AUDIO OSCILLATOR

3 OUTSTANDING NEW FEATURES:

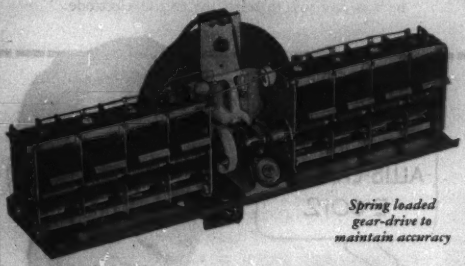
1. ACCURATE CONTROL DIAL
EASY TO READ • NO PARALLAX

2. RUGGED CONSTRUCTION

3. IMPROVED CIRCUIT



New friction driven dial provides hair-line accuracy



Spring loaded gear-drive to maintain accuracy

Rugged chassis construction on heavy cast frame

The Model 200-I is a resistance-tuned audio oscillator designed to provide high stability and accuracy for use in frequency measurements. It has a range from 6 cps to 6000 cps,* divided into six frequency ranges as follows: 6 to 20, 20 to 60, 60 to 200, 200 to 600, 600 to 2000 and 2000 to 6000 cps. Each of these ranges has an individual frequency adjustment so that the instrument may be set to a frequency standard such as the -*hp*- Model 100-B.

The large, 6-inch diameter, main frequency dial is calibrated over approximately 300 degrees, making possible a large number of calibrated points to cover the entire range. The dial itself rotates behind a fine wire locator which is visible through an opening in the panel. Parallax is completely eliminated and calibrations are spread over an effective scale length of nearly eight feet. Fast and extremely accurate settings are made easily with this dial. There are two manual controls: one direct action, and the second for vernier adjustments. An electronically regulated power supply is included to assure greatly improved stability.

The Model 200-I -*hp*- Audio Oscillator is but one among many new -*hp*- instruments which are to make public appearance as the cloak of military secrecy is removed. Preliminary technical information is available on this instrument now ...write for it! And watch for the early release of other new -*hp*- instruments.

**This frequency coverage was selected for interpolation work. Other frequency ranges can be supplied from 6 cps to 100 kc on special order.*

hp

HEWLETT-PACKARD COMPANY
P. O. Box 930B, Station A • Palo Alto, California

930

DON'T LET OLD-FASHIONED RESISTORS CRAMP YOUR ENGINEERING STYLE!

The only Resistors wound with CERAMIC-INSULATED WIRE

INSULATION APPLIED BEFORE WIRE IS WOUND

A Major Resistor Improvement—*Not just a minor change*

Don't waste time engineering "around" the handicaps imposed by conventional resistors! Use Sprague Koolohms and get exactly what you want.

No power resistor can be one whit better than the insulation given its windings—and Koolohm ceramic insulation applied to the wire before it is wound gives you the maximum in this respect. Koolohms can be used safely up to their full rated wattage values. Their use of insulated wire permits larger wire sizes to be used, and guards against shorts and changed values. They give more resistance in smaller size, and are readily adaptable to almost any mounting style best suited to your production.

Standard Sprague Koolohms include 5- to 120-watt power types. Other Sprague Resistors include bobbin types, hermetically sealed power resistors, 5- to 150-watts, and meter multipliers. Write for new catalog—just off the press.

SPRAGUE ELECTRIC COMPANY, Resistor Division
(Formerly Sprague Specialties Co.)
North Adams, Mass.

ARMY E NAVY

SPRAGUE *KOOLOHMS

Totally Different . . . Outstandingly Superior

*TRADEMARK REG. U. S. PAT. OFF.

STACKPOLE

CONTINUOUSLY ADJUSTABLE CARBON RHEOSTATS

(CARBON PILES)

Under impetus of war requirements demanding resistance adjustments for more critical, more precise, smoother, and more dependable control than is possible with conventional variable resistance units, Stackpole engineering has developed the Continuously Adjustable Carbon Rheostat formed of carbon disc piles to a high degree of efficiency Simply by changing the pressure applied to the pile, every possible resistance value within its range is available without opening the electrical circuit in which it is connected. The pressure to vary the resistance to the most critical adjustment may be applied electrically, mechanically, centrifugally or hydraulically. Uses range from both generator and line voltage regulator applications to remarkable speed control through governed field current on motors. Many other projects incorporating the Carbon Pile Resistor are now in the development stage.

Stackpole regularly supplies Carbon Piles in practically any length pile and diameter required. Resistance ranges have been materially expanded and a greater degree of resistance variation may now be obtained in a pile of a given size. Careful engineering control of manufacture assures a high degree of uniformity on a quantity production basis. Write for bulletin giving complete data.

CARBON DISCS FOR OTHER APPLICATIONS

Other Stackpole types include carbon discs for electric brakes for trucks, speed governors—or wherever a little power must control a lot of power with utmost precision, smoothness, and dependability.

STACKPOLE CARBON COMPANY

St. Marys, Pa.

OTHER STACKPOLE PRODUCTS

BRUSHES - CONTACTS *(All carbon, graphite, metal, and composition types)* IRON CORES RARE METAL CONTACTS
WELDING CARBON PRODUCTS VOLTAGE REGULATOR DISCS BATTERY CARBONS
PACKING, PISTON, and SEAL RINGS POWER TUBE ANODES, etc.

Typical of the many varieties of Permanent Magnets designed and made by Cinaudagraph

Unmagnetized . . . none

Magnetized . . . $\frac{1}{4\pi}\int_0^{\circ} H \cdot dB$ **ergs/c.c.**

After Years . . . no loss of service

Don't blame us for the queer looking formula. Our engineers told us one day that it is the amount of energy we put into our magnets. Three hours of pencil chewing and six aspirin tablets later, we gave up the whole thing as a bad job, and are passing it on to you. They said they'll be glad to explain it, so drop us a line. We'll get out of range and act as referee.

CINAUDAGRAPH CORPORATION

8 SELLECK STREET STAMFORD, CONNECTICUT

12-CC-4

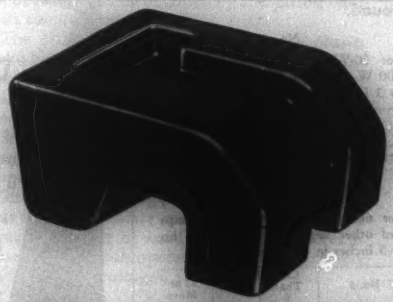
CINAUDAGRAPH CORPORATION

Specialists for over a generation in

OIL IMMERSED MOTOR CONTROL

ROWAN CONTROL

THE ROWAN CONTROLLER CO., BALTIMORE, MD.



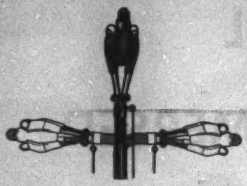
This is a THIRD RAIL INSULATOR

• Odd shapes and sizes,—variety in design is our specialty. Our production equipment and facilities are not limited to "round insulators". And regardless of size or shape you'll find Universal "dry process" porcelain to be of uniform high quality, having high dielectric strength; will withstand thermal shock and arcing; non corrosive; resists acids and will not carbonize. Send blueprints of your requirements.

THE UNIVERSAL CLAY PRODUCTS CO.

1560 EAST FIRST STREET SANDUSKY, OHIO

MATTHEWS HOLDFAST LAMP CHANGERS



Removes and replaces lamps in high places, such as ceilings, side walls, electric signs, etc. Like a human hand on the end of a wooden pole. Saves time and prevents ladder accidents.

To remove or replace lamps from side walls or at an angle, pull cord attached to the swivelled ring. This bends the wristlike coil spring so that the Changer will work just as well at a right angle to the rotating pole as in vertical position.

Shipping weight each, 1 pound.

No. 2

For 50-Watt Rough Service, 15 to 100 Watt Mazda and other lamps up to 3 inches in diameter.

No. 2	Less Than 6	6 to 11	12 or More
Price Each	$5.00	$4.75	$4.50

No. 3

For 60 to 500 Watt Mazda Lamps and other large and odd shapes up to 5 inches in diameter.

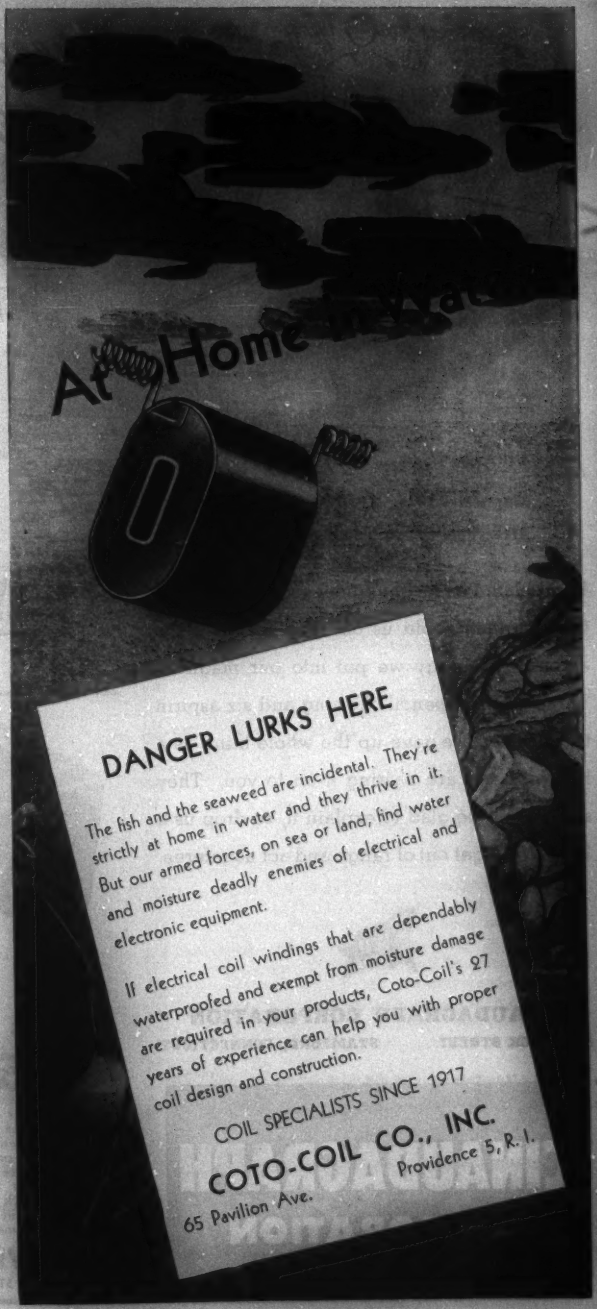
No. 3	Less Than 6	6 to 11	12 or More
Price Each	$5.50	$5.25	$5.00

All Prices F.O.B. St. Louis, Mo.

Specially treated wood handles can be furnished in 6-foot sections at $3.75 per section including couplings.

Your Electrical Supply Jobber Will Fill Your Order.

W. N. MATTHEWS CORPORATION
ST. LOUIS, U. S. A.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The fish and the seaweed are incidental. They're strictly at home in water and they thrive in it. But our armed forces, on sea or land, find water and moisture deadly enemies of electrical and electronic equipment.
If electrical coil windings that are dependably waterproofed and exempt from moisture damage are required in your products, Coto-Coil's 27 years of experience can help you with proper coil design and construction.
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TYPE 50XBX103

D.P. D.T. main contacts, rated 6 amps. at 24 volts DC. 3 3/16" long; 1 7/8" high; 1 5/8" wide.

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Simplified Interlock—Symmetrical Design

Sturdily constructed to aviation specifications, and of immensely simplified design, Series 50XBX 2-coil Relays are an important addition to the well-known line of Struthers-Dunn "Memory" types. A new style positive interlock between the two symmetrical operating elements represents latch-in relay construction in its simplest, most dependable form. This latch requires no extraneous parts other than integral extensions of the sturdy coil "armatures" themselves. It operates positively from a momentary impulse and a minimum of power. Application of power to one coil latches the contacts into one position. Power then applied to the other coil throws the contacts into a latched-in second position. A third "unlatched" position, valuable for certain applications, can be obtained by energizing both coils simultaneously.

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Struthers-Dunn Memory Relays of this general type are produced in ratings from 6 to 200 amperes or more, and with practically any desired contact arrangement. Standard types provide for two auxiliary contacts, one in each coil circuit. The use of auxiliary contacts makes it possible to obtain operation over an extremely wide range of voltages, a-c or d-c.

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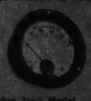

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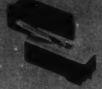

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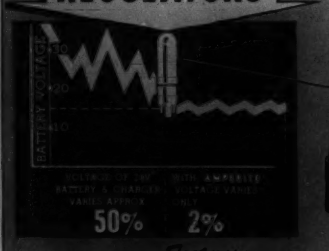

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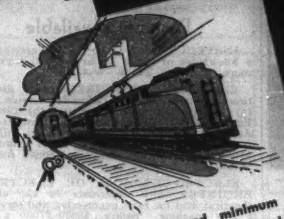

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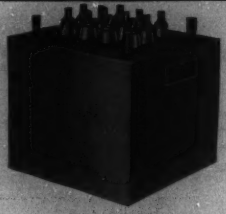

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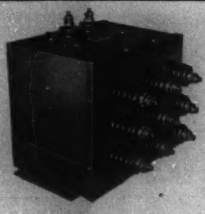

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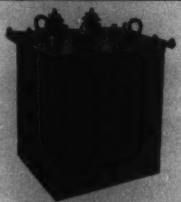

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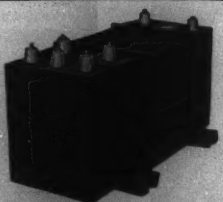

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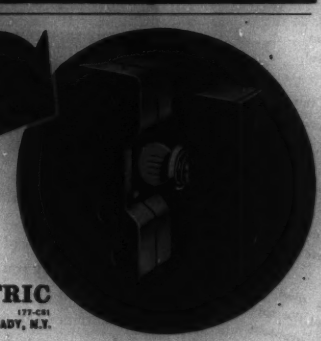

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A graduate electrical engineer, 30 to 40 years of age, possessing supervisory ability, experienced in the design, layout, and specification of electrical equipment for chemical manufacturing plants.

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Give full experience, education, age, present salary and salary expected. Enclose snapshot.

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ENGINEERS. (a) Designer, electrical graduate, 30–40, experienced in the design, layout and specification of electrical equipment for chemical manufacturing plants. Should be well grounded in the fundamentals of electrical theory, and have a working knowledge of practical electrical problems. Location, Delaware. (b) Power, Mechanical or Electrical Engineers, 26–35, with aptitude and experience in heat balance thinking, for work devoted to plant improvements, results engineering and effecting economy in the generation and consumption of steam, electricity, compressed air, water and refrigeration. Locations, throughout the United States. Apply by letter, giving age, experience, education, present and expected salary and enclose a snapshot. W-4632.

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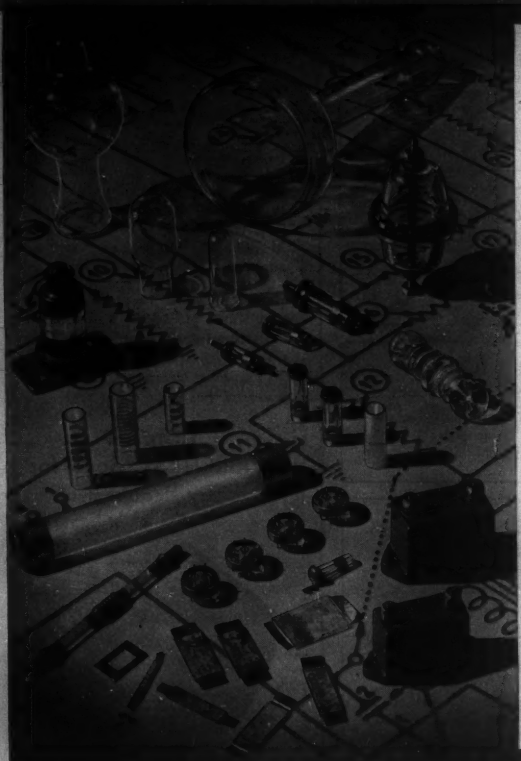

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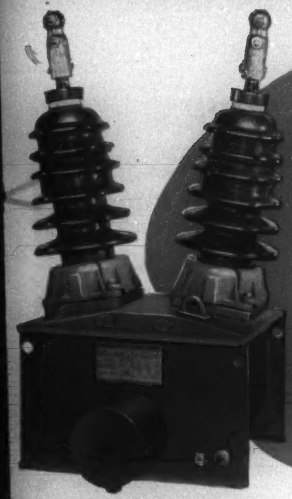

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ASA Accuracy Class	0.3	0.3	0.3	0.3

This means that with standard ASA burdens the ratio correction factor and the transformer correction factor will be within the limits of the ASA accuracy class 0.3.

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FOR A BETTER UNDERSTANDING OF ACCURACY CLASSIFICATION

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GENERAL ELECTRIC

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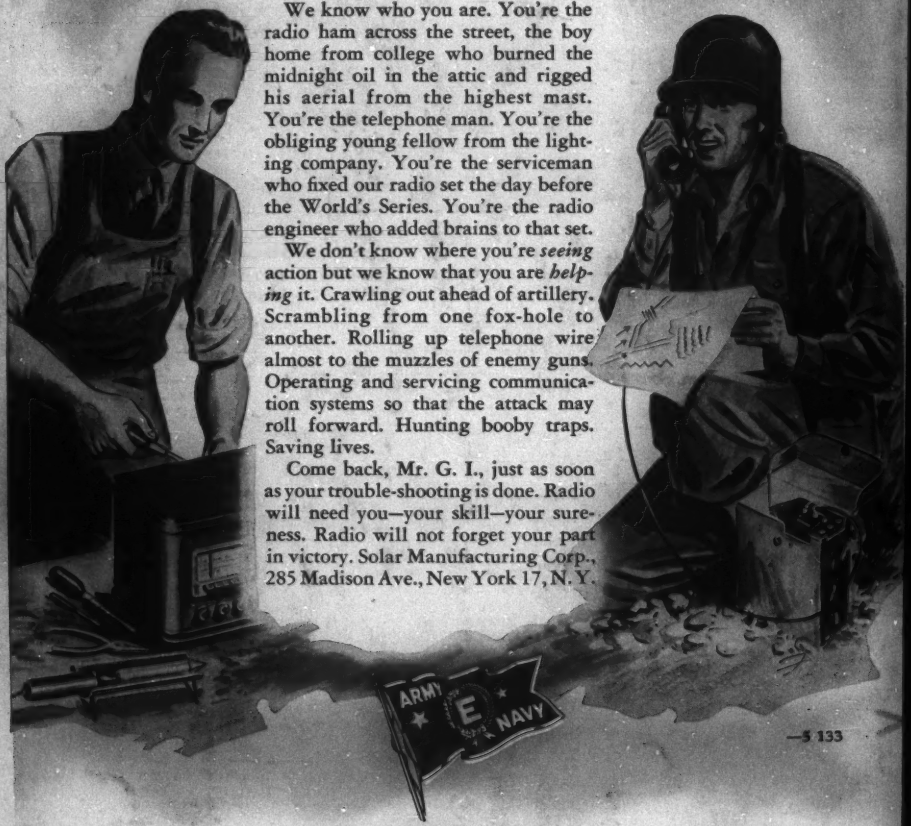
MR. TROUBLE-SHOOTER



Thanks, Mr. G. I. You're close to our thoughts. All of us in radio know the world-wide job you're doing in the Signal Corps.

We know who you are. You're the radio ham across the street, the boy home from college who burned the midnight oil in the attic and rigged his aerial from the highest mast. You're the telephone man. You're the obliging young fellow from the lighting company. You're the serviceman who fixed our radio set the day before the World's Series. You're the radio engineer who added brains to that set.

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